# NAVAL POSTGRADUATE SCHOOL

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# THESIS

**FACTORS INFLUENCING THE STRUCTURE OF THE MONTEREY BAY SEA BREEZE**

by

Emily M. Duvall

March 2004

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**13. ABSTRACT (maximum 200 words)**

The Monterey Bay sea breeze varies because of the influence of features such as inversions, clouds, synoptic-scale flow, and topography. The sea breeze is important because it impacts fire weather, air pollution, agriculture, and aviation operations, among other things. Analyses are conducted using a multi-quadric based program, which incorporates aircraft data, surface observations, and profiler data, to investigate the Monterey Bay sea breeze during 01-31 August 2003. Factors including inversions, cloud cover, amount of heating, distribution of heating, synoptic-scale flow, and topography are studied to determine their influence on the sea breeze. Six days are selected that best illustrate the factors that influence the structure of the Monterey Bay sea breeze. Results show that offshore flow weakened the strength of the sea breeze and decreased the depth. A cooling trend in surface temperatures at the end of August also weakened the strength of the sea breezes and decreased the depth. Clouds are present during this period, which influenced the amount of heating, and consequently, the sea breeze response. The presence of a marine layer weakened the thermal gradient that in turn, weakened the sea breeze circulation.

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# FACTORS INFLUENCING THE STRUCTURE OF THE MONTEREY BAY SEA BREEZE

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# ABSTRACT

The sea breeze is a thermally induced circulation that arises along essentially every coastline. However, the Monterey Bay circulation associated with the sea breeze varies day to day because of the influence of features such as inversions, clouds, synoptic-scale flow, and topography. Understanding the sea breeze is important because it impacts fire weather, air pollution, agriculture, and aviation operations, among other things.

Analyses are conducted using a multi-quadric based program to investigate the Monterey Bay sea breeze during 01-31 August 2003. This program incorporates aircraft data, surface observations, and profiler data. Outputs from the analysis program are plotted in VISUAL to characterize the structure of the sea breeze. Factors including inversions, cloud cover, amount of heating, distribution of heating, synoptic-scale flow, and topography are studied to determine their influence on the sea breeze.

Six days are presented in this thesis that best illustrate the factors that influence the structure of the Monterey Bay sea breeze. Results show that offshore flow weakened the strength of the sea breeze and decreased the depth, as expected. A cooling trend in surface temperatures at the end of the month also weakened the strength of the sea breezes and decreased the depth. Clouds are present during this period, which influenced the amount of heating, and consequently, the sea breeze response. The presence of a marine layer weakened the thermal gradient that in turn, weakened the sea breeze circulation.

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# I. INTRODUCTION

## A. MOTIVATION

The sea breeze is an important influence on coastal weather, climate, and in some regions, air quality. Previous studies have discussed how the sea breeze relates to problems such as air pollution transport, location and initiation of convection, aviation safety, gliding and sailing, and forest fire forecasting (Simpson 1995). Those studies have used various meteorological models to understand this event better. Many types of instruments have been used to measure the horizontal and vertical extent of the sea breeze, including advanced platforms such as aircraft and gliders, lidar, and Doppler radar, to the more traditional method of radiosondes.

Sea breezes are a thermally direct, diurnally reversible circulation in the vertical plane (Atkinson 1981) that appear to be simple, however many components of the circulation have been difficult to measure in detail. The lack of data over water makes it difficult to ascertain the structure of the sea breeze in that area. Other factors such as terrain make the sea breeze more complex. The development of Doppler lidar has allowed researchers to observe the land-sea breeze cycle in detail (Darby et al 2002). Aircraft and gliders offer the possibility of more comprehensive measurements (Simpson 1995).

To emphasize the importance of understanding and forecasting the sea breeze, air quality will be discussed. Air pollution is often enhanced by the sea breeze. For example, NOAA's Environmental Technology Laboratory studied the ozone pollution in New England during 2002 (ETL 2004). The goal of the program was to better understand the land-sea breeze circulation and its role in distributing pollutants throughout New England. Those particles that are small enough to float with the air will be transported inland within the onshore flow layer of the sea breeze, and recirculate within the sea breeze cell. Other particulates will be dispersed inland. A follow-on study will be performed in 2004. Although Monterey Bay is not a region with high air pollution, understanding the sea

breeze and its local modifying effects is critical because of the prescribed burns that take place at Fort Ord (Gahard 2003).

Taking the air quality issue one step further, recent historical events point to the critical role of technology in the war against terrorism and of homeland protection. Major U.S. cities that lie along all coastlines have now become targets of terrorism, including both biological and chemical war. The sea breeze becomes a key role in pollutant dispersion because it can distribute the toxin plume inland over heavily populated areas (or out to sea). Being able to accurately forecast the sea breeze, along with the ability to identify the outcome when toxins are added to the atmosphere becomes crucial to homeland defense.

The Department of Defense (DOD) currently uses three primary dispersion models, including the Hazard Prediction and Assessment Capability (HPAC) that provides the means to accurately predict the effects of hazardous material released into the atmosphere and its impact on civilian and military populations. "Relevant real-world hazard prediction requires timely and accurate weather data in the area of concern (DTRA 2004)." The other models are: the Emergency Management Information System (D2PUFF), and the U.S. Navy's Chemical/Biological Agent Vapor, Liquid, and Solid Tracking model (VLSTRACK) (Ross 2003). Many military operations are conducted near coastal areas where conditions change constantly, so it is obvious how forecasting and understanding the modifying effects of the sea breeze have become necessary in the present-day warfare regime.

## B. OBJECTIVES

Monterey is an area of complex terrain (Figure 1). Topography influences the sea breeze circulation, as demonstrated by Darby et al (2002). The local topography allows for mountain and valley flows that have an impact on the development of the sea breeze. These interactions, including terrain and coastline shape, will be further addressed in a later section.

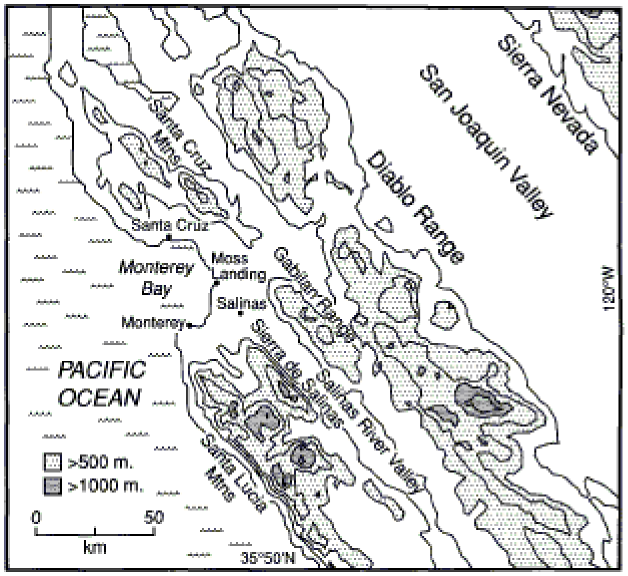


Figure 1. Map of the Monterey Bay region with complex terrain. (From Banta et al 1993)

During August 2003, the Autonomous Ocean Sampling Network (AOSN) II field experiment in Monterey Bay, funded by the Office of Naval Research, was conducted. The project, hosted by the Monterey Bay Aquarium Research Institute (MBARI), studied the bay to observe and predict the upwelling of coastal waters that occurs off Monterey Bay during the summer months. Various instruments were used to study the phenomenon, including aircraft flights over the bay. The flight data consisted of many parameters (including latitude and longitude, air temperature, wind direction and speed, relative humidity, and pressure) that could be easily accessed at the Naval Postgraduate School. The flight data enables measurements to be recorded over water that aid in the understanding of the local sea breeze.

The present study uses aircraft flight data from August 2003 along with other measurements to analyze the sea breeze circulation for that time period. The goal of this research is to analyze how the synoptic-scale flow, distribution and depth of heating, inversions, cloud cover, and topography modify the Monterey Bay sea breeze. The research will also compare past studies to

determine how the complex terrain affects the sea breeze and to see how well the sea breeze in the Monterey Bay area adheres to the basic conceptual model of a sea breeze circulation.

# II. BACKGROUND

## A. BASIC CIRCULATION

The absence of a synoptic-scale flow results in the fundamental pattern of the sea breeze. As daytime heating occurs, the land temperatures exceed adjacent water temperatures, creating a coastal thermal gradient to which the wind responds. The direction of the wind associated with the sea breeze is directed inland along the surface pressure gradient, which is oriented perpendicular to the coastline. The lack of synoptic flow or significant topography will cause the wind direction of the sea breeze to be dependent only on the orientation of the local coastline (COMET 2003).

Sea breeze strength is proportional to the thermal gradient. As solar heating intensifies, the corresponding pressure gradient increases by lowering the surface pressure over land relative to the pressure over water. At higher levels, offshore flow is produced by the opposite direction of the pressure gradient. A response to this increased pressure gradient will be seen in the magnitude of the sea breeze. Vertical motions are provoked in response to the horizontally flowing air and continuity considerations. Onshore flow causes air from higher levels to sink, replacing the air removed from the surface. Convergence inland causes air to rise and replace the air that is being removed aloft. The onset of the sea breeze is usually indicated by an increase in wind speed, a temperature decrease, and a rise in humidity (Atkinson 1981).

In late afternoon, the sea breeze reduces and eventually ends after sunset. The land cools, and the pattern reverses to form a land breeze circulation (COMET 2003). Land breezes are just as important, however the focus of this study will be on the sea breeze itself.

## B. MODIFYING EFFECTS: SYNOPTIC-SCALE FLOW

There are many factors that influence the sea breeze circulation. Regional features such as terrain, coastline orientation, and the presence of low-level inversions help determine the local circulations associated with the sea

breeze (COMET 2003). Although each factor is important in understanding the sea breeze, the core of this research is to study the modifying effect of the synoptic-scale background flow. Other influences will be briefly examined as well.

Numerous studies have researched the impact of the synoptic flow. The study performed by Estoque (1962) used four directions of the background flow to learn the effect of the prevailing conditions on the evolution of the sea breeze circulation. The directions consisted of onshore, offshore, parallel to coast with land on the left, and parallel to coast with land on the right. The results of Estoque (1962) demonstrate the impact of the background flow on the intensity, extent, and shape of the sea breeze circulation in the absence of terrain.

Optimal conditions for a sea breeze consist of weak synoptic-scale offshore flow, a deep layer of heating, and a compressed thermal gradient at the coastline. However, sea breezes can be found when the imposing background flow is relatively strong and varies in direction. In Estoque's (1962) case of offshore wind, the sea breeze was not observed as early as the no wind case. As the day progressed and heating intensified, a strong horizontal temperature gradient was produced from the advection of warmer air over the land towards the sea. A corresponding pressure gradient was then generated in the surface layers. The response was onshore flow near the surface, which penetrated inland only 8 km. Similar to the case mentioned above, strong vertical motions occurred, however, there was noticeable return flow aloft.

Onshore synoptic flow prevents the development of the horizontal temperature gradient from land to sea, which deters the associated horizontal pressure gradient. Consequently, this reduces the chance for the development of a sea breeze (Atkinson 1981). Estoque's (1962) onshore wind case demonstrated that advection inhibits an increase in temperature of the atmosphere over land, thus creating a weaker pressure gradient and weaker circulation. By afternoon, stronger low-level onshore flow was present, and no vertical motion occurred.

In Estoque's (1962) study, flow parallel to the coast had similar effects to that of onshore and offshore cases, but depended on the direction of the wind. When the wind direction blew along the coast with land to the right, the horizontal pressure gradient was strengthened, thus resembling the sea breeze produced by offshore winds. The sea breeze penetrated inland 18 km, farther than that of the offshore case, and strong vertical motion was present. In the case of land to the left, the effected sea breeze mimicked the onshore flow situation. For this case, vertical motion existed, and the thermal gradient intensified inland from the coast.

Arritt (1993) used a database of 31 sea breeze simulations to examine the effects of large-scale flow on the characteristics of the sea breeze. The results were summarized into four categories: onshore synoptic flow, calm to moderate opposing synoptic flow, strong opposing synoptic flow, and very strong opposing synoptic flow. Sea breeze strength was larger in the case of weak, opposing synoptic flow than for no background flow. "Such a response suggests that the interaction between the thermally induced perturbation and the large-scale flow is significantly nonlinear (Arritt 1993)." Large-scale flow in the same direction as the sea breeze suppressed the thermally forced flow perturbation, unless the onshore flow was less than 3 m $s^{-1}$. Opposing flow of 6 m $s^{-1}$ enabled the sea breeze to reach the coastline, however, a well-developed sea breeze circulation existed entirely offshore when large-scale offshore flow was strong (> 6 m $s^{-1}$).

> These results suggest that the absence of an onshore component at the coastline does not necessarily indicate the absence of a sea breeze circulation. Although observations over the water are much rarer than over land, there is evidence that sea or lake breezes can in fact remain entirely offshore in the presence of opposing synoptic flow (Lyons 1972).

Arritt (1993) analyzed the inflow-layer depth and discovered that offshore flow reduced the inflow-layer depth. Once the sea breeze reached the coastline, the inflow-depth increased very quickly. When stronger opposing flow was present the depth increased until around sunset; the depth stopped rising around noon when calm or weak opposing flow was present. Arritt's (1993) study, along

with Bechtold et al (1991), discovered vertical motion to be the largest when the propagation speed of the sea breeze balanced the opposing background flow, creating a sea breeze that was stationary with the coastline.

Another important feature of weak opposing flow is the effect on the potential temperature gradient. "The largest values of potential temperature gradients coincided with the sea breezes that just reached the coastline (Arritt 1993)." Weak, opposing flow created the strongest sea breeze that just reached the coastline. When the opposing synoptic flow was so strong that no sea breeze formed, there was a great decline in the potential temperature gradient. Offshore flow has the potential to push the thermal (and associated pressure) gradient out to sea, thus creating a sea breeze that begins several kms out, often not reaching land until mid-afternoon (Atkinson 1981).

In summary, Arritt's (1993) study found that onshore synoptic flow perturbed the thermal gradient enough to significantly weaken the sea breeze. Calm to moderate opposing flow caused an increase in the temperature gradient, and inland penetration of the sea breeze. The effect of strong opposing flow on the sea breeze inhibited inland penetration. Finally, when very strong opposing synoptic flow was present, no sea breeze formed. Since these results were for flat terrain, a goal of this study is to determine the extent to which similar effects occur for the Monterey Bay region with complex terrain.

### C. MODIFYING EFFECTS: CLOUDS

Clouds will often form as a result of the sea breeze, and clouds can also alter the circulation. Cloud-free days generate the strongest heating, which provide the potential for a strong sea breeze circulation. When clouds are present, the daytime heating is inhibited and cooling is limited at night. On days when there is clearing throughout the afternoon, the thermal gradient may be enhanced due to the presence and persistence of clouds over water therefore delaying the timing of the sea breeze (Nuss 2003).

The sea breeze can affect the development and location of convection and occurrence of coastal fog and stratus (COMET 2003). Cloud development

frequently occurs in the ascending part of the sea breeze circulation, while clouds tend to dissipate over sea, where the air is sinking. Convection created by upward vertical motion at the sea breeze front will cause the formation of clouds. If there is inland penetration of the sea breeze, fog and stratus may develop due to increased dew points and nighttime cooling. The Florida peninsula is an example of a region where summer convection is common. The convective activity is heightened due to interaction between the sea breeze front and convergence zones and even other sea breeze fronts. This process usually occurs in late afternoon when sea breeze penetration is furthest. In California, this period is associated with gusty, strong winds and onshore advection of marine stratus (COMET 2003).

### D. MODIFYING EFFECTS: INVERSIONS

Low-level inversions influence the development of sea breezes. A shallow inversion will limit the vertical depth of the heating, which generally reduces the sea breeze strength. A capping inversion may restrict convective activity by restricting the ascent of buoyant air parcels. The associated lift with a sea breeze may not be enough to break through the inversion and trigger convection.

In Southern California, air quality conditions are influenced by many factors including inversions and sea breezes. A temporary inversion is created by a warm air mass descending over the cool, moist marine layer produced by the interaction between the ocean's surface and the atmosphere's lowest layer. This capping inversion prevents pollutants from dispersing upward and allows pollutants to accumulate within the lower layer (City of Carson 2004). The sea breezes disperse the pollutants throughout the region. In general, the sea breeze tends to relieve areas of high pollution by transporting air away from the city (Atkinson 1981).

The inversion is well known to central California. For example, marine stratus and fog develops from moisture being trapped by the inversion. "Lifting and/or cooling of the boundary layer leads to the formation of coastal fog or stratus (COMET 2003)." Inversions play a big role in the development and

evolution of the sea breeze in the Monterey Bay area. The effects of the inversion and its role in modifying the heating and sea breeze strength will be discussed in a later section.

### E. MODIFYING EFFECTS: COASTAL CHARACTERISTICS

The geometry of the coastline plays a significant role in the sea breeze circulation. In order for the sea breeze to develop, usually the isotherms must be parallel to the shore, creating a thermal gradient that is perpendicular to the coastline. The shape of the coastline may enhance or reduce the convergence and convection found along the sea breeze front (COMET 2003). As described in Nuss (2003), concave coastlines such as the Monterey Bay tend to produce a sea breeze that is diffluent over the land areas. This type of flow inhibits convergence and uplift found along the front. However, for coastlines that are shaped in a convex manner such as capes and peninsulas, the sea breeze is convergent over the land. This convergence enhances upward vertical motion, which increases cloud formation.

Terrain features such as coastal mountains can also modify the evolution of the sea breeze. Mountains and associated valleys can contribute to early development of the sea breeze by producing mountain-valley circulations that add to the sea breeze (COMET 2003). A coastal mountain range enhances the temperature contrast between the sea and land by preventing the inland advancement of cooler marine air. Sloping terrain affects the timing and depth of the sea breeze. Inland valleys that have significant heating attract the sea breeze further inland. Once the sea breeze begins, hills and valleys may affect its direction (Atkinson 1981). Through channeling effects, the sea breeze may be rotated into an along-valley direction as the sea breeze penetrates inland (Nuss 2003). Low, strong marine inversions favor such steering effects, forcing the sea breeze around hills rather than over them (Atkinson 1981).

A study by Darby et al (2002) focused on the behavior of the diurnal flow along the central coast of California that is driven by the land-sea contrast and two mountain ranges. Terrain sensitivity studies (10 model simulations) were

performed to understand the role of complex terrain east of Monterey Bay on the vertical structure of the sea breeze, and compared to lidar data obtained on 16 September 1987. Coastal mountains and hot inland valleys characterize central California. Previous studies on the sea breeze performed at Monterey Bay discovered that a shallow sea breeze develops early in the day, followed by a deeper sea breeze later. The study by Darby et al (2002) hypothesized that a local-scale temperature contrast at the shoreline drives the earlier, shallow sea breeze, whereas a larger-scale temperature contrast between the cooler ocean water and the hot interior valley of central California drives the deeper sea breeze that develops later.

The results of Darby et al (2002) showed that the complex terrain surrounding the Monterey Bay causes the sea breeze to be more complex than predicted by theory. A conceptual model of the sea breeze was produced from knowledge of the evolution of the vertical structure. Sea breeze forcing occurred on two length scales, the first being the length between the ocean and coastal mountains, and a second larger scale between the ocean and taller inland mountains. Model results demonstrated that the slope flows produced by each mountain impacted the structure of the sea breeze flow near the surface and the expected return flow aloft.

> The coastal mountain generated a weak slope flow approximately 1500 m deep, producing the larger-scale onshore flow seen in the lidar sea breeze measurements. The land-water contrast was responsible for the shallow sea breeze. The presence of the inland mountain, representing the Sierra Nevada range, greatly influenced the flow above 1500 m ASL. Since simulations with the inland mountain produced westerly flow above 1500 m and simulations without it had easterly flow at these heights, this topographic feature clearly affected winds near the shore even though it was hundreds of km inland (Darby et al 2002).

Results showed the interaction between the coastal and inland mountains enhanced the onshore flow in the morning hours. The interaction between terrain and the land-water contrast had a strong impact in the afternoon, opposing the sea breeze flow. In the morning, the coastal mountain slope flow

enhanced the sea breeze flow, but the mountain obstructed its progress in the afternoon. The interaction between coastal and inland mountains and the land-water contrast enhanced onshore flow at the surface for the entire time period analyzed (Darby et al 2002).

A goal of this study is to expand on the previous studies, especially those performed in the Monterey Bay region, and to add to the knowledge of the sea breeze. Where Darby's study mainly focused on the influence of the complex terrain on the sea breeze, the research presented here will include that aspect along with effects of the synoptic flow, inversion and clouds.

Additionally, results of this study will be compared to both Arritt (1993) and Estoque (1962), who did not include complex terrain in their investigations, but provided insight into the conceptual model for the sea breeze. This study will attempt to determine if the complex topography surrounding Monterey Bay has an impact on the sea breeze evolution relative to synoptic forcing. Thirty-one days from August 2003 will be used to characterize the sea breeze evolution under a variety of conditions. The range of synoptic-scale flows and marine layer depths will be used to compare to similar results from these previous studies.

# III. METHOD OF ANALYSIS

## A. ANALYSIS PROGRAM

A multi-quadric based analysis program called 3dmq, written by Dr. Wendell Nuss, is used in this study to conduct analyses in order to investigate the sea breeze in Monterey. The program was run for each day in August 2003 at 12Z and 21Z to determine the structure prior to the sea breeze (12Z) and near its peak (21Z). 3dmq is a spatial analysis program that uses three-dimensional interpolation to combine scattered observations with a model first guess into a three-dimensional analysis onto a specified grid. This program requires a set of input files that establish the analysis grids, observation information, first guess information, and parameters that adjust aspects of the analysis. Explanations of the files are given below, as described by Dr. Nuss (Nuss 2004).

This analysis program runs on a UNIX machine and requires that the following files be located in the directory where the program runs. The first file, “run3dmq”, is a script file that organizes the input files for a specified analysis day and time and runs the program. The information file, “analgrd.inf_rt”, specifies the grid information and characteristics on which the analysis is done. “Guessgrd.inf_rt” specifies the necessary information about the first guess grid to be used in the analysis. The file “analparms.inf_rt” sets the adjustable parameters that are used for this case. “Batch3d_rt” specifies the information about observation file types and directory locations that are used for the analysis. This file allows certain observations to be “turned off or on” when necessary. The last file, “terrain.grd_rt”, is a terrain grid for the analysis grid.

The present study analyzes two time periods each day. The 12Z analysis uses the 12-hour forecast from the 00Z model run as the model first guess, and the 21Z analysis uses the 9-hour forecast from the 12Z run as the model first guess. The 3mdq program outputs a log file containing information from the

analysis program, a set of numeric files that contain observations used in the analysis, and files that contain the gridded analysis in three dimensions such as winds and temperature.

Seven output files are generated that are used for the study of the sea breeze. These files incorporate observations from various sources, which are described in a later section. The gridded files consist of height, sea level pressure, surface pressure, temperature, dew point, and winds (u and v component).

## B. VISUAL

VISUAL is a diagnostic and display program that uses NCAR graphics utility routines to examine meteorological observations and grids (Nuss and Drake 1995). The program enables the user to produce different types of plots with various parameters. The information generated from the 3dmq analysis program is displayed with VISUAL to diagnose the sea breeze characteristics. Examples of these figures from VISUAL will be shown later. The display program can also create hardcopies of each plot.

## C. TYPES OF DATA

### 1. Surface Observations

The surface observations used in this study consist of a combination of many sources. These observations are input into the analysis program through the batch3d_rt file. The observations come from the following: National Weather Service (NWS), National Data Buoy Center (NDBC), California Department of Forestry (CDF), AWS Convergence Technologies, Inc. (formerly Automated Weather Source, Inc), and various local sensors maintained by the Naval Postgraduate School.

### 2. NPS Profiler

Data from the Naval Postgraduate School's wind profiler is input into the analysis program through the batch3d_rt file. The 915 MHz Doppler Wind Profiler is located at 36.69$^{o}$ N latitude, 121.76$^{o}$ W longitude, just north of the

Marina Municipal Airport (Gahard 2003). For this study, data from the profiler that are analyzed consist of wind speed, wind direction, and virtual temperature. Inversion heights, determined from the profiler plots, are also used in this study.

Wind speed and direction is determined as a function of antenna beam positioning, backscatter from wind advected turbulence-size irregularities in the index of refraction, Doppler theory, and signal processing (Gahard 2003). Virtual temperature is computed by the radio acoustics sounding system within the profiler by measuring the speed of sound (Gahard 2003).

Dick Lind, NPS Department of Meteorology, provided the outputs from the wind profiler. Each plot is a time series, indicating winds and temperature every thirty minutes over a twenty-four hour period (Gahard 2003). The time series begins at 1630 local time and ends at 1600 local time on the following day, with time increasing to the left. The hatched region is the mixing height, computed by using the surface virtual temperature. Every image represents the surface to 5000 feet above sea level. Figure 2 is an example of a profiler plot. Temperature is indicated by color and wind barbs follow the standard convention.

### 3. Aircraft Data

A UV-18A Twin Otter aircraft (figure 3) collected data during August 2003 for the AOSN II experiment, in collaboration with CIRPAS (Center for Interdisciplinary Remotely-Piloted Aircraft Studies). The Twin Otter functions as a sensor platform with an integrated data acquisition system (CIRPAS 2004). Todd Anderson, NPS Department of Oceanography, is in charge of the aircraft data and has generated various plots from each flight (figure 4). The heavy black line indicates the flight path, color represent air temperature, and the arrows symbolize surface wind. The flight path shown is representatative of the paths taken by the aircraft throughout the experiment. Flight levels varied from day to day, however, surface and cross-section wind fields generated by 3dmq were reflective of the atmosphere for the specified time.

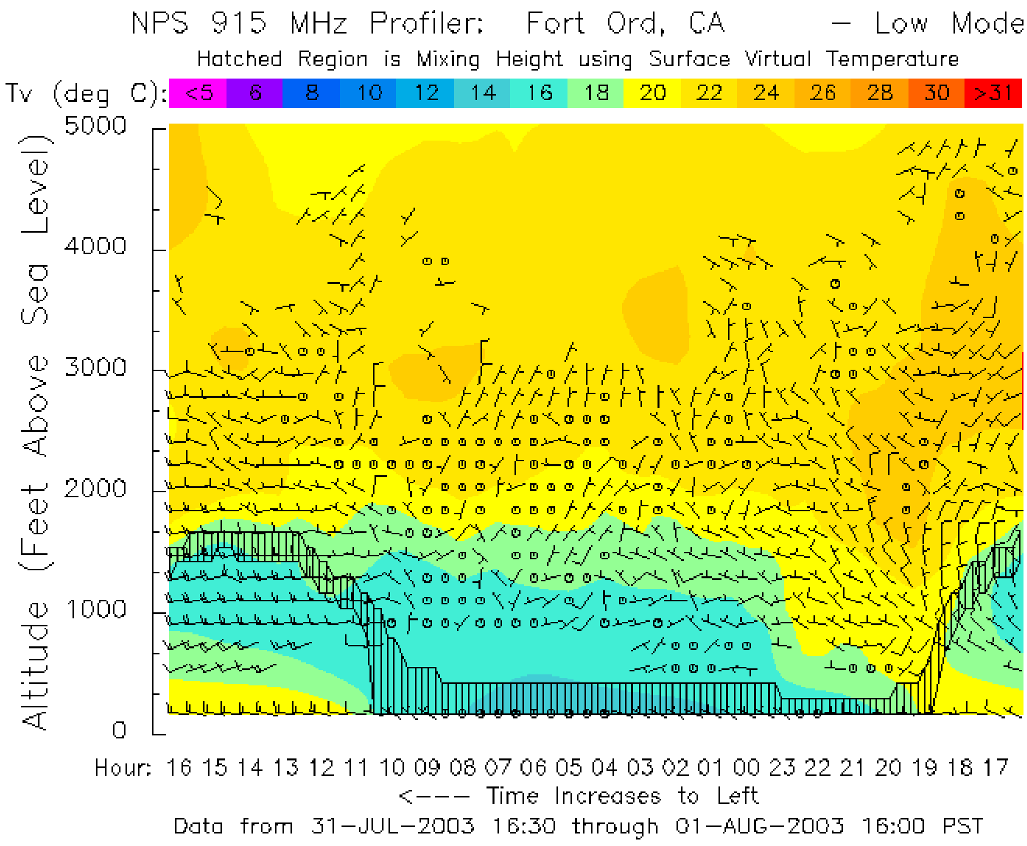


Figure 2. Profiler Data for 01 August 2003. (From: Lind 2003)


Figure 3. UV-18A Twin Otter. (From: CIRPAS 2004)

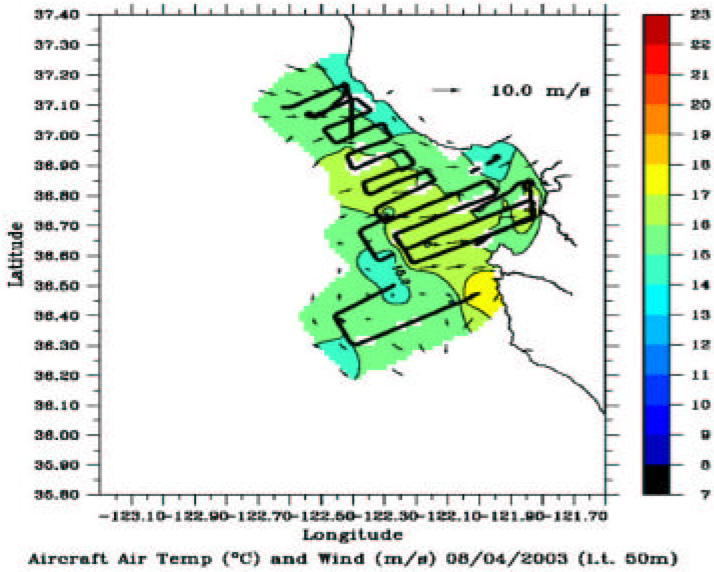


Figure 4. Aircraft Air Temperature and Wind of Monterey Bay for 04 August 2003. (From: Anderson 2004).

Data from the flights is input into the 3dmq analysis program for the 21Z analysis through the batch3d_rt file. Although this study analyzes the sea breeze in Monterey for each day of August 2003, Twin Otter flights did not occur every day. Table 1 lists the flight schedule. Three days (August 24,26, and 28 2003) of extensive study in this thesis do not have aircraft data.

| Day of Flight (2003) | |
|---|---|
| 4-Aug | 15-Aug |
| 5-Aug | 20-Aug |
| 6-Aug | 21-Aug |
| 10-Aug | 22-Aug |
| 11-Aug | 25-Aug |
| 13-Aug | 29-Aug |

Table 1. Twin Otter flight schedule for August 2003.

## D. SATELLITE IMAGERY

Satellite imagery is used to determine cloud cover and the effects on the sea breeze. One-km visible imagery taken from the GOES-10 (or GOES- West) satellite is used for this analysis. The archived imagery is viewed in GARP (GEMPAK Analysis and Rendering Program).

## E. MM5 MODEL

The Mesoscale Model Version 5 (MM5), run at NPS, is used for the analysis first guess and for obtaining the synoptic flow at 850 mb. MM5 was developed at Penn State University (PSU) and at the National Center for Atmospheric Research (NCAR), and is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulations (PSU/NCAR 2004). The model is triple-nested; coarse grid resolution is 108 km (59 x 59 grid points), fine grid resolution is 36 km (49 x 61 grid points), and superfine grid resolution is 12 km (91 x 127 grid points). Figure 5 shows the location of the nests, run at NPS twice daily. The MM5 model contains thirty vertical levels and uses multi-quadric interpolation (2D) to convert first guess grid fields and observations to MM5 grid fields (Miller 2004).

MM5 requires lateral boundary conditions to run because it is a regional model. Therefore, it is coupled with a global model and uses that output as a first guess for objective analysis or as the lateral boundary conditions (PSU/NCAR 2004). In this case, the AVN (Aviation) model provides the boundary conditions for the MM5 36 hour forecast.

## F. PROCEDURE

The purpose of this thesis is to characterize the Monterey Bay sea breeze evolution relative to a variety of factors. This research also takes into account earlier findings from previous studies to verify these results. The period from 01-31 August 2003 was selected to study those effects because of the availability of a large amount of aircraft data and the existence of strong sea breeze forcing.

After running the analysis program for 12Z and 21Z, horizontal plots of surface winds and temperature were generated on a Monterey Bay area map background. The plots were created in VISUAL to examine the direction and strength of the sea breeze, as well as to categorize the thermal gradient intensity and orientation (relative to the coastline).

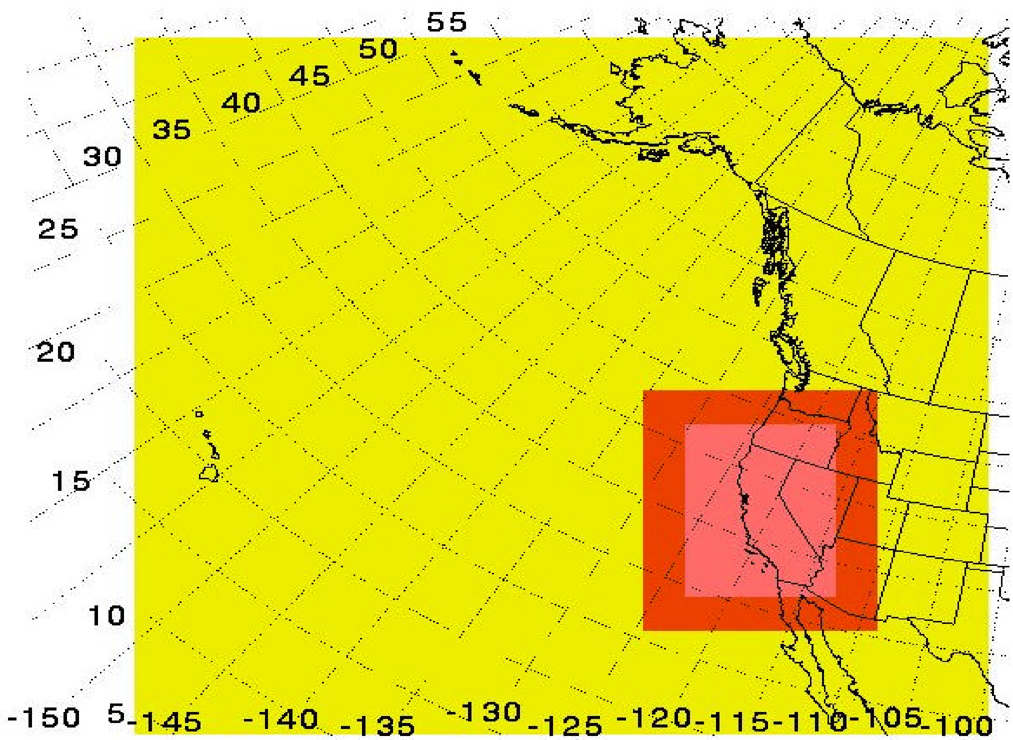


Figure 5. Model nested grid and domain sizes. (From Miller 2004)

Additionally, using the output from the analysis program, cross-section plots were produced in VISUAL to inspect the vertical structure of the sea breeze. The cross-section used in this study begins in the Monterey Bay and extends inland to Chualar (figure 6), approximately 49.8 km. These plots consist of potential temperature and winds. Potential temperature (theta), rather than temperature, is used because it is helpful when determining the stability of the atmosphere. Cross-section winds are actually circulation vectors. The VISUAL program calculates vertical motion based on convergence and/or divergence. The circulation vectors are generated from the horizontal wind component in the

plane of the cross-section and the vertical component; VISUAL then plots a resultant vector (the circulation vector). See Figure 7. Vectors that point down imply subsidence, whereas upward pointing vectors suggest upward motion.

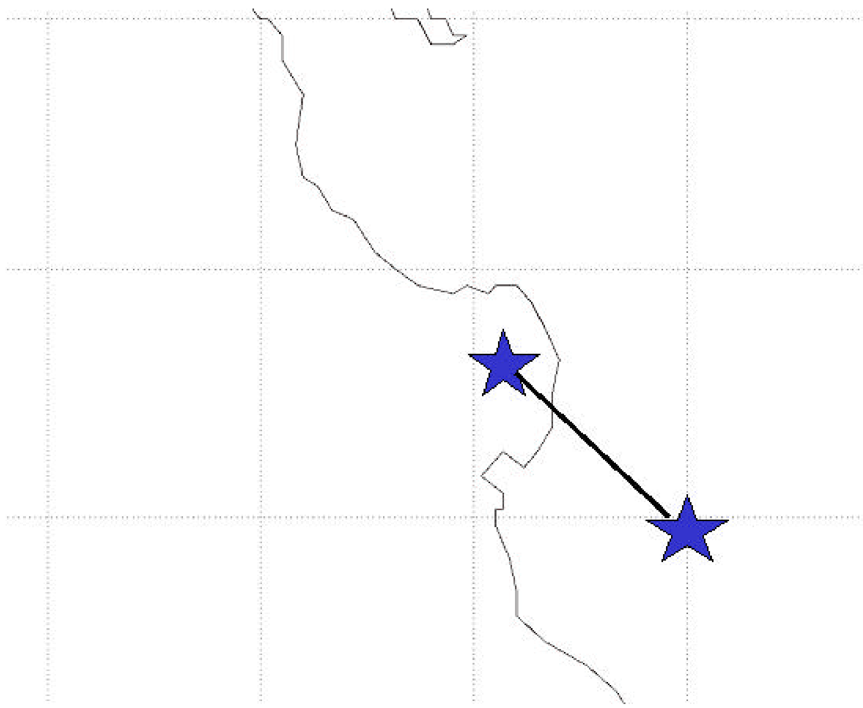

Figure 6. Path used for cross-section plots.


Figure 7. Example of a circulation vector in the x,z plane.

Furthermore, the synoptic-scale flow pattern of 850 mb was examined from the MM5 model, and was plotted in GARP. The days were categorized into flow that was similar in direction to the sea breeze, opposed the sea breeze, or was parallel to the coast. Strength of the synoptic flow was characterized into weak flow (< 5 knots), moderate flow (5-10 knots), and strong flow (> 10 knots).

Profiler data was used to verify the flow pattern observed in the horizontal plots. The profiler data was also used to identify inversions, the inversion height, depth of heating, and depth of the sea breeze layer. Comparisons were made between profiler plots and cross-sections of theta and circulation vectors to evaluate the above parameters. Also, satellite imagery was reviewed for each day beginning at 17Z through 21Z. The GOES-10 imagery shows the degree of cloud cover and was valuable for determining whether or not clouds played a role in modifying the sea breeze.

The final step consists of producing temperature difference plots in VISUAL. The purpose of this was to highlight the diurnal effects. VISUAL calculates the difference in temperature between 21Z and 12Z and plots the vertical structure of the temperature change during the nine hours that is caused by diurnal changes. Temperatures over land are expected to increase, indicated by positive values (solid lines). Little change is expected over water and above 900 mb. A change above this height may mean that adjustments are being made from something other than the typical diurnal effects that cause temperature fluctuations (i.e., synoptic evolution).

Information was gathered twice daily for each day of August 2003, and was placed into spreadsheets to help summarize the sea breeze features that are described in this section. This helps to recognize consistency, patterns, and other relevant information. It also assists in choosing specific days that were analyzed in further detail during this study, which will be explained in the next chapter.

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# IV. DATA ANALYSIS AND RESULTS

## A. INTRODUCTION

The evolution of the sea breeze circulation in the Monterey Bay region differs from day to day. Previous studies (Arritt 1993; Bechtold et al 1991; Estoque 1962) have identified interaction with the synoptic scale, static stability, clouds, as well as other factors as modifiers of the basic sea breeze circulation. To begin to characterize the impact of these factors on the Monterey sea breeze, each day in August 2003 was examined to determine the nature of these factors on that day.

Table 2 lists the essential parameters that were considered for each day. First, the orientation of the thermal gradient with respect to the coastline was analyzed on the horizontal plots. Days when the isotherms remained parallel to the Monterey Bay coastline were labeled as “with coast thermal gradient,” and days when the temperature gradient shifted to a more southwest to northeast pattern were labeled as “northeastern orientation.” Second, the sea breeze strength was examined on the horizontal plots. Focusing on the winds in the Monterey Bay and directly at the shoreline, the wind speed for each day at 21Z was entered into the table. Third, the synoptic-scale flow was reviewed in GARP, using the nine-hour 12Z MM5 model forecast of the 850 mb wind speed and direction. Direction of the flow was determined by drawing a compass rose on each 850 mb plot, dividing it into eight quadrants (Table 3), and establishing the direction based on the quadrant in which the wind barb pointed from. Fourth, one km visible satellite imagery was examined for each day to examine cloud cover over the coastal zone. If clouds were present, “yes” was entered in the table; if there was not any cloud cover, “no” was entered; and clearing in the afternoon was listed as “yes, clearing.” The last parameter entered in the table was inversion base height, determined from the profiler images at 21Z.

A careful review of the thirty-one days on table 2 shows the complex nature of the Monterey Bay sea breeze. No obvious relationships between sea

breeze strength and the various factors emerge. To use the data, comparative case studies were formed from six days of the month. These six were chosen for extensive analysis because they best illustrate the resultant sea breeze due to the modifying effects.

The following days were analyzed in further detail because they illustrated examples that had one varying parameter, while the other parameters were not present or reduced in magnitude. The characteristics of the sea breeze for the selected days were examined and compared to each other and to 05 August to highlight the importance of specific factors. Fortunately, 05 August was a "classic" sea breeze day with no significant modifying factors, and also it represented well the sea breeze conceptual model. Synoptically, 05 August exhibited weak onshore flow; the absence of an inversion allowed for a deep layer of heating; there was a moderately strong thermal gradient oriented with the coastline; and a sea breeze of 15 knots. 22 August was selected to emphasize the importance of the synoptic-scale flow on modifying the sea breeze. On 22 August the background flow was offshore and the sea breeze decreased to 5 knots. 24 August was chosen because it illustrated the impact of the low-level thermal structure evolution. The thermal gradient was oriented towards the northeast on this particular day, and the layer of heating was very shallow (in the absence of clouds) due to a developing inversion. The result was a 15-knot sea breeze. On 26 August the synoptic-scale flow changed to onshore, and both an inversion and clouds modified the sea breeze by decreasing the strength somewhat. 28 August had background flow that was light and from the south; a deeper inversion; cooler surface temperatures (clouds were present); a weakened thermal gradient, and increased sea breeze strength. 29 August had weak offshore synoptic-scale flow; an inversion with cooler surface temperatures (again, clouds were present), and a decrease in sea breeze strength.

| DAY | THERMAL GRADIENT ORIENTATION | SEA BREEZE STRENGTH | 850 MB DIRECTION | 850 MB SPEED | CLOUDS | INVERSION BASE |
|---|---|---|---|---|---|---|
| 1 | with coast | 10 | 135-180 | 5 | yes | 1400 FT |
| 2 | with coast | 10 | 180-225 | 10 | yes | 2000 FT |
| 3 | with coast | 10 | 135-180 | 5 | yes; clearing | 1800 FT |
| 4 | with coast | 10 to 15 | 135-180 | 5 | yes; clearing | NONE |
| 5 | with coast | 15 | VAR | LIGHT | no | NONE |
| 6 | with coast | 15 | VAR | LIGHT | yes; clearing | NONE |
| 7 | NE tilt | 15 | 180-225 | 5 | no | NONE |
| 8 | NE tilt | 15 | 315-360 | 5 | no | 1000 FT |
| 9 | NE tilt | 10 to 15 | 180-225 | 5 | no | 1000 FT |
| 10 | NE tilt | 10 to 15 | VAR | LIGHT | no | 1000 FT |
| 11 | slight NE tilt | 15 | 315-360 | 5 | no | 800 FT |
| 12 | slight NE tilt | 10 to 15 | 0-45 | 5 | yes; clearing | 800 FT |
| 13 | with coast | 10 | VAR | LIGHT | yes; clearing | 800 FT |
| 14 | slight NE tilt | 5 to 10 | 225-270 | 5 | yes; clearing | 1800 FT |
| 15 | with coast | 10 to 15 | 270 | 5 | no | 1000 FT |
| 16 | with coast | 10 | 270-315 | 5 | yes;some clearing | 1000 FT |
| 17 | with coast | 15 | 0-45 | 5 | yes | 1000 FT |
| 18 | slight NE tilt | 10 | 45-90 | 5 | **no image avail** | 1400 FT |
| 19 | with coast | 10 | 135-180 | 5 to 10 | yes | 2400 FT |
| 20 | with coast | 10 to 15 | 135 | 25 | yes;clearing | 1800 FT |
| 21 | with coast | 5 to 10 | 135-180 | 25 | yes;clearing | 3000 FT |
| 22 | with coast | 5 | 135-180 | 10 to 15 | yes;some clearing | NONE |
| 23 | with coast | 10 to 15 | 90-135 | 10 | no | 1000 FT |
| 24 | slight NE tilt | 15 | 90-135 | 10 | no | 1000 FT |
| 25 | with coast | 10 | 90-135 | 10 | no **** | 1000 FT |
| 26 | slight NE tilt | 10 | 180-225 | 10 | yes;some clearing | 1000 FT |
| 27 | slight NE tilt | 10 to 15 | 225-270 | 5 | yes;some clearing | 1400 FT |
| 28 | slight NE tilt | 10 to 15 | VAR | LIGHT | yes;some clearing | 2000 FT |
| 29 | slight NE tilt | 5 to 10 | 0-45 | 5 | yes;some clearing | 1800 FT |
| 30 | with coast | 10 to 15 | 90-135 | 5 | yes | 1400 FT |
| 31 | with coast | 5 to 10 | 135-180 | 5 | **no image avail** | 1400 FT |

Table 2. Example spreadsheet of parameters.

| Quadrant | Direction |
|---|---|
| I | 0-45 |
| II | 45-90 |
| III | 90-135 |
| IV | 135-180 |
| V | 180-225 |
| VI | 225-270 |
| VII | 270-315 |
| VIII | 315-360 |

Table 3. List of quadrants.

## B. 05 AUGUST 2003

05 August was chosen to be the reference day for the case studies that are described in the following section. This day best represents the "classic" sea breeze so it is helpful to compare the 5$^{th}$ to selected days to illustrate how various factors modify the Monterey Bay sea breeze.

The 850 mb winds in the Monterey Bay, as well as most of the region, on 05 August at 21Z are light (< 5 knots) and from the southwest (figure 8). This corresponds to light, onshore synoptic flow. Despite the direction, the sea breeze seems to remain free from the effects of the synoptic flow due to the small magnitude of the flow.

Figure 9 is a vertical cross-section at 21Z that shows the vertical depth of the sea breeze. Cross-sections used in this study were constructed from the 3dmq analyses and depict potential temperature (lines) and circulation vectors (arrows) from the surface to 700 mb. The cross-sections were chosen to slice through the atmosphere near the profiler (used in the analysis) at a specific time. Monterey Bay is on the left of the image and Chualar is on the right. Profiler images were compared to cross-section plots to examine various aspects of the vertical structure; the former illustrate the change in temperature and winds in the vertical with respect to time, and the latter provide a spatial view of potential temperature and winds at a specific time. Cross-sections of theta were also useful in determining the stability of the atmosphere, however, the instability near 1000 mb on figure 9 is an artifact of the model first guess field. Similar effects were seen on other cross-sections. Both types of plots were appropriate for examining the depth of the sea breeze and depth of heating. On 05 August, the depth of the sea breeze circulation was about 900 mb, with strongest winds near the surface. Aloft, the downward pointing arrows suggest that there was a broad region of subsidence over the coastal zone.

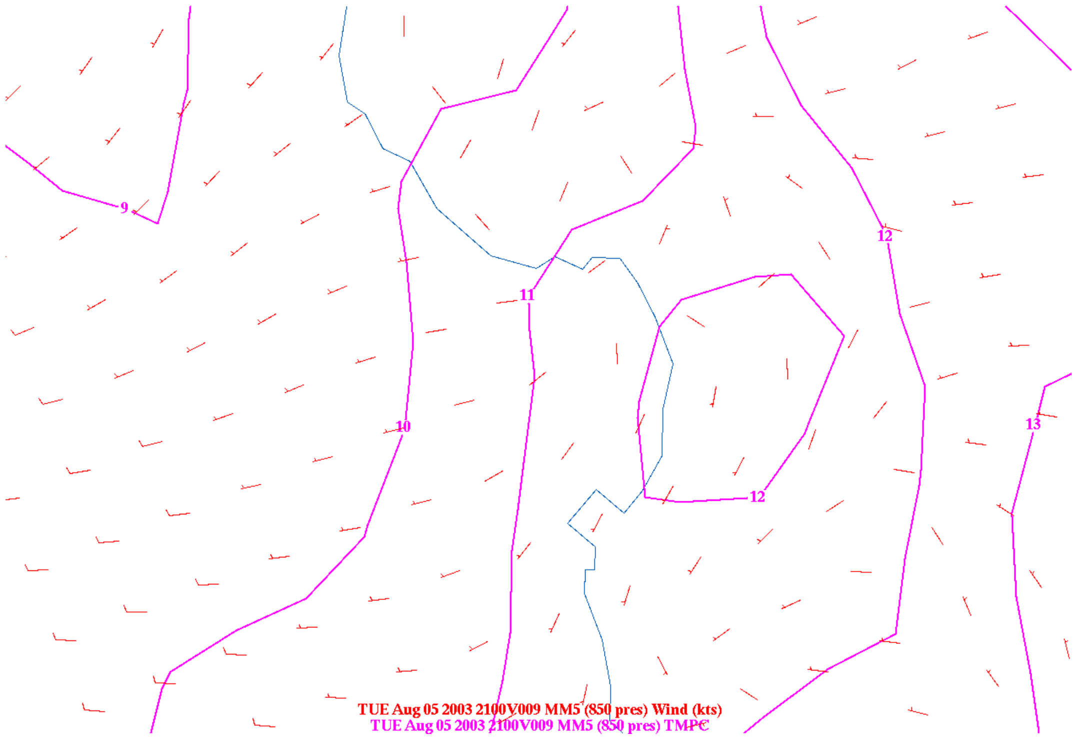


Figure 8. 850 mb winds for 05 August 2003 at 21Z

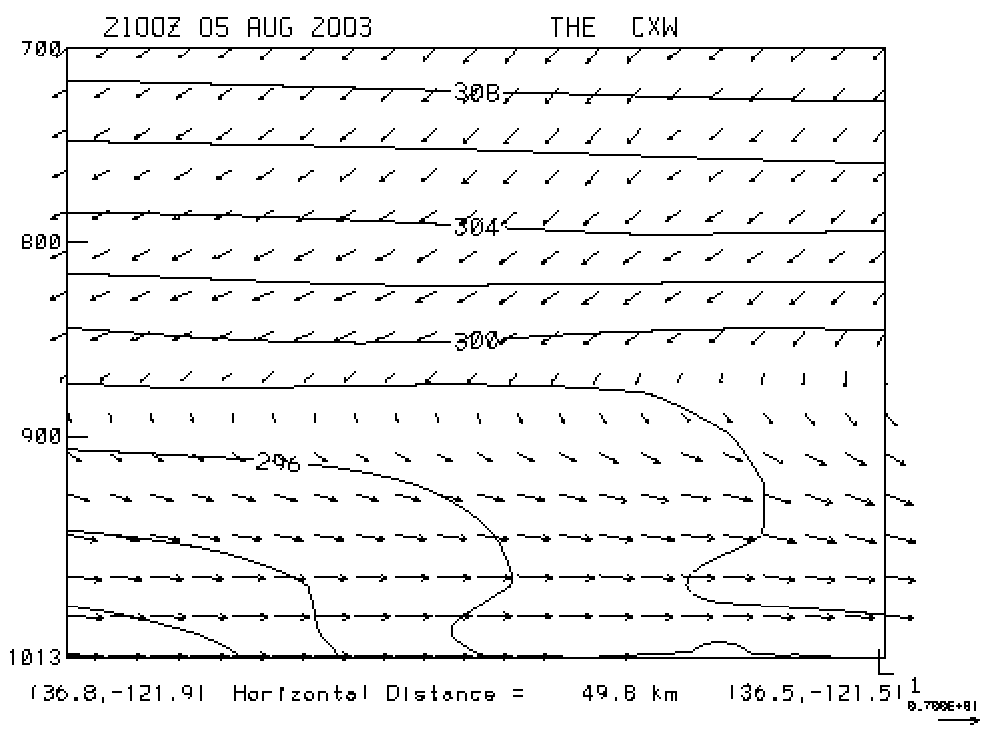


Figure 9. Vertical cross-section of potential temperature (K) and circulation vectors for 05 August 2003 at 21Z.

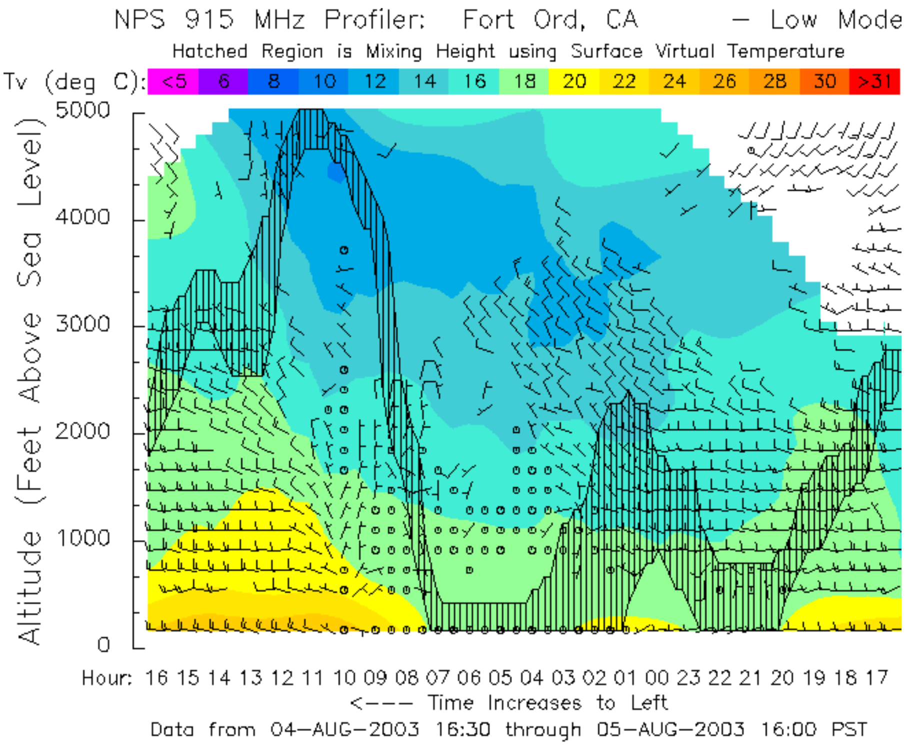


Figure 10. Profiler image for 05 August 2003. (From: Lind 2003)

The profiler image of 05 August (figure 10) shows the depth of heating that occurred throughout the day. Surface temperatures rose to approximately 24$^{o}$ C at 1400 PST (21Z), from 18$^{o}$ C at 0500 PST (12Z). The layer of heating ascended to about 1500 feet (ASL) at 1300 PST. This image also gives information on the depth and time evolution of the sea breeze. The sea breeze began at 1000 PST, with increasing strength throughout the afternoon. It deepened rapidly with time, ultimately reaching about 3000 feet (ASL), and had decreasing wind speed aloft.

Figure 11 illustrates the sea breeze strength and direction in the Monterey Bay, and shows the strength and orientation of the thermal gradient. In the bay, the sea breeze was 15 knots on 05 0August, with a direction of 270$^{o}$ at almost all points along the bay. The thermal gradient was of moderate strength, and was primarily oriented perpendicular to the coast around the entire bay.

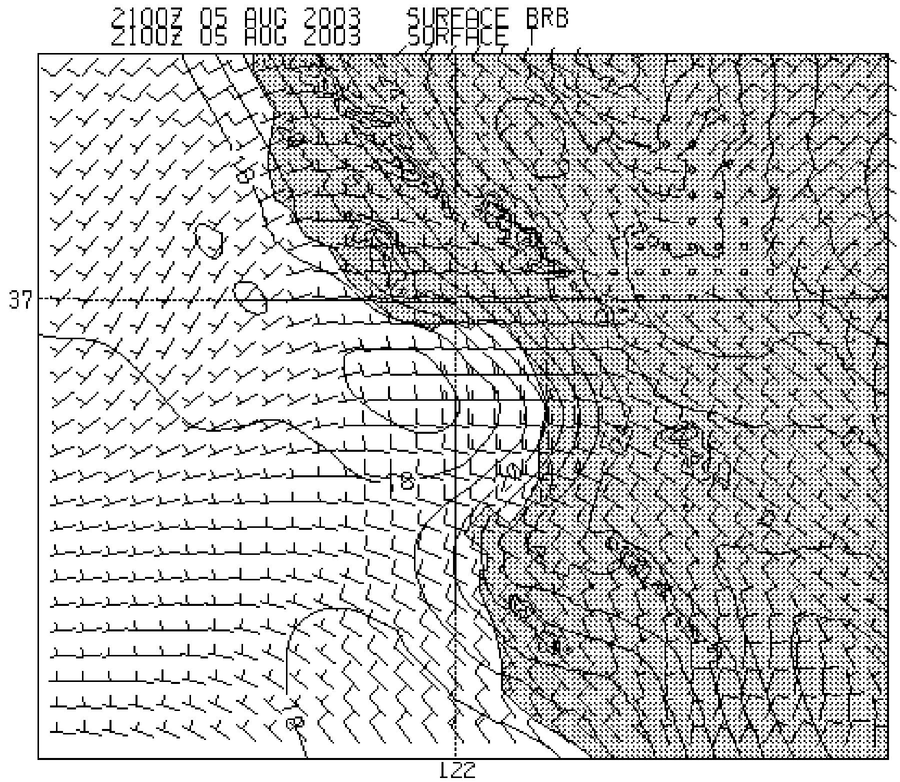


Figure 11. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 05 August 2003 at 21Z.

## C. COMPARATIVE CASE STUDIES

### 1. Comparison Case One: 05 vs. 22 August 2003

Case one illustrates the impact of the synoptic flow on the sea breeze circulation. The synoptic flow was characterized by examining the 850 mb winds (knots). For locations close to sea level (Monterey), the 850 mb chart represents the top (or close to the top) of the planetary boundary layer and is a good representation of the synoptic flow. On 22 August (figure 12), the wind speed ranges from 10-15 knots and was from the southeast across the entire region, corresponding to offshore synoptic flow in the bay. 05 August had light (< 5 knots) onshore flow at 850 mb. Satellite imagery (not shown) for 05 August depicted no clouds, whereas clouds existed earlier in the day on 22 August, but began to clear by the analysis time of 21Z.

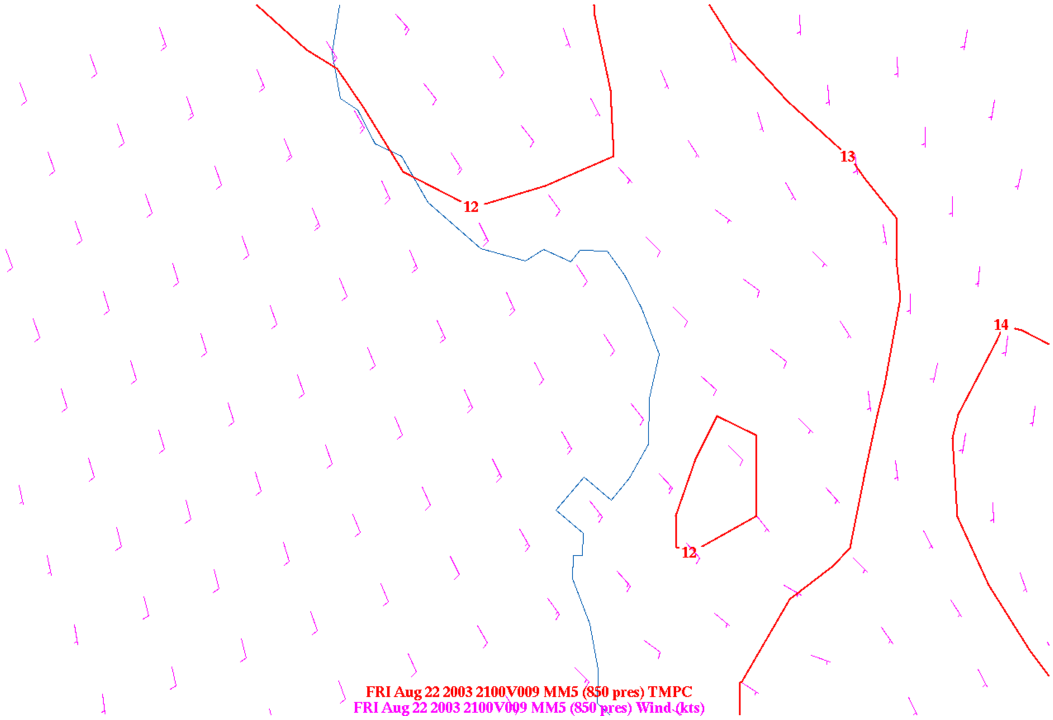


Figure 12. 850 mb winds for 22 August 2003 at 21Z

The surface plot of temperature and wind speed at 21Z on 22 August (figure 13) illustrates the strength and direction of the Monterey Bay sea breeze. 05 August had a sea breeze of about 15 knots, with a direction of approximately 270$^{o}$ over most of the bay, whereas the sea breeze on 22 August was 5 knots (in the bay) and has varying wind directions that tend to point across the coast all around the bay. The effect of the strong (10-15 knots) offshore flow caused the intensity of the sea breeze to decrease in comparison with the light onshore flow.

Another difference between 05 and 22 August was the strength of the thermal gradient. Similar temperatures existed over the water for both days; however, land temperatures for 05 August were 24$^{o}$ C and greater compared to about 22$^{o}$ C on the 22$^{nd}$. This created a stronger temperature gradient for 05 August. The orientation of the isotherms was similar for both days – parallel to the coastline around the bay, creating a thermal gradient that is perpendicular to the coastline.

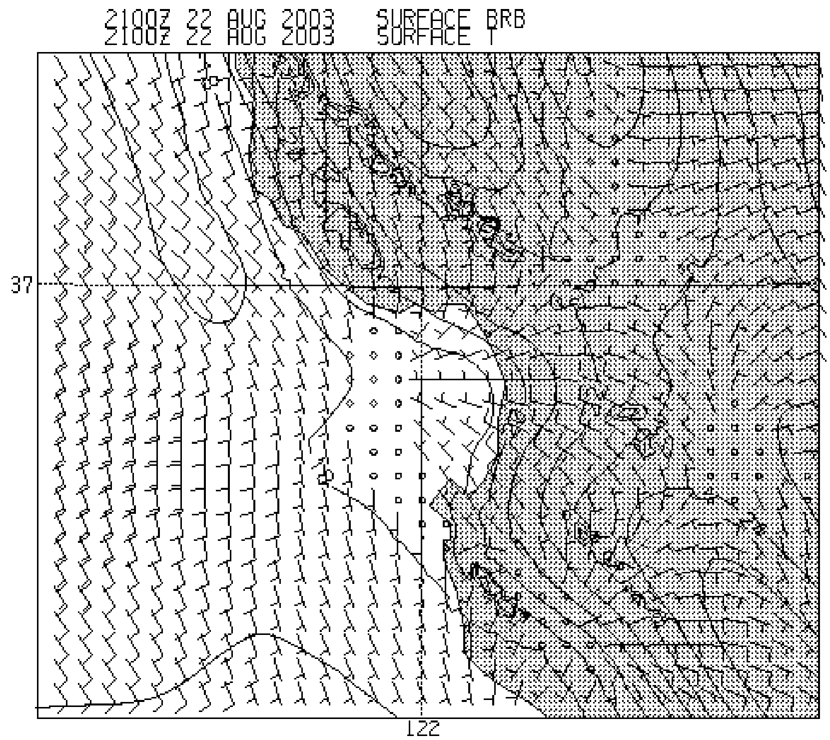


Figure 13. Horizontal surface plot of temperature ($^{o}$ C) and wind speed (knots) for 22 August 2003 at 21Z.

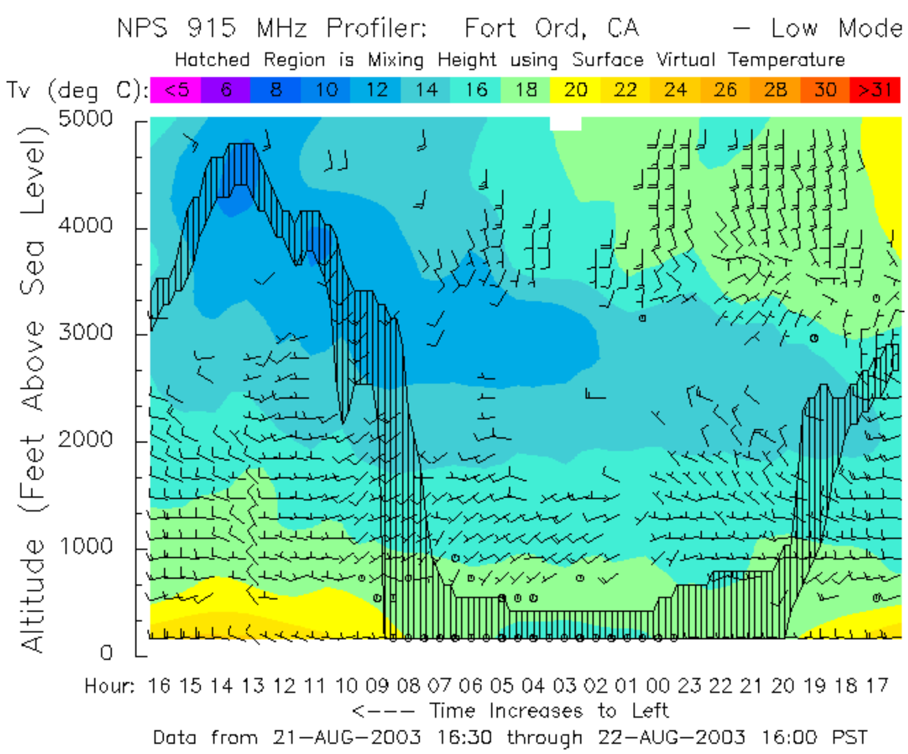


Figure 14. Profiler image for 22 August 2003. (From: Lind 2003)

The profiler image (figures 14) depicts the evolution of the thermal structure in the vertical throughout the day. The analysis time for the sea breeze was 21Z; profiler time is given in PST, which corresponds to 1400 PST. Both images are similar for that time, as well as the rest of the day. On 22 August, a surface inversion was present in the early morning hours, but disappeared before 0600 PST. Heating was confined to a shallow layer near the surface, with surface temperatures reaching $22^{o}$ C by 21Z. 05 August had a deeper layer of heating, with similar surface temperatures.

The profiler plots also give some indication of the vertical depth and evolution of the sea breeze. 22 August had a slightly shallower sea breeze of 2500 feet (ASL) compared to 3000 feet (ASL) on 05 August (figure 10). Both days had a sea breeze that deepened over time; it began around 1000 PST on 05 August; on 22 August it appears to have begun a few hours earlier. When the sea breeze began on August 22, the surface winds were at 5 knots. The winds gained strength throughout the afternoon until the sea breeze reached 10 knots at the surface at 21Z. Speed continued to increase past the 21Z analysis time to 15 knots. Aloft, the sea breeze strength was similar to that reported at the surface throughout the afternoon, however, on the $5^{th}$ winds tend to increase aloft over time.

The static stability of 22 August (figure 15) was slightly less (below 850 mb) than the stability of 05 August (figure 9). Also, subsidence has depressed the $300^{o}$ K line, producing a slightly warmer lower atmosphere for the $5^{th}$. The cross-section for 22 August depicts offshore flow aloft, agreeing with the southeasterly flow that was represented at 850 mb. The offshore flow was a combination of both synoptic-scale flow and return flow from the sea breeze. Notice how weaker offshore flow was present around 875 mb, with stronger offshore flow above. The weaker vectors are most likely indicative of the return flow. At lower levels, the depth of the onshore flow (sea breeze) was similar to 05 August, reaching approximately 900 mb.

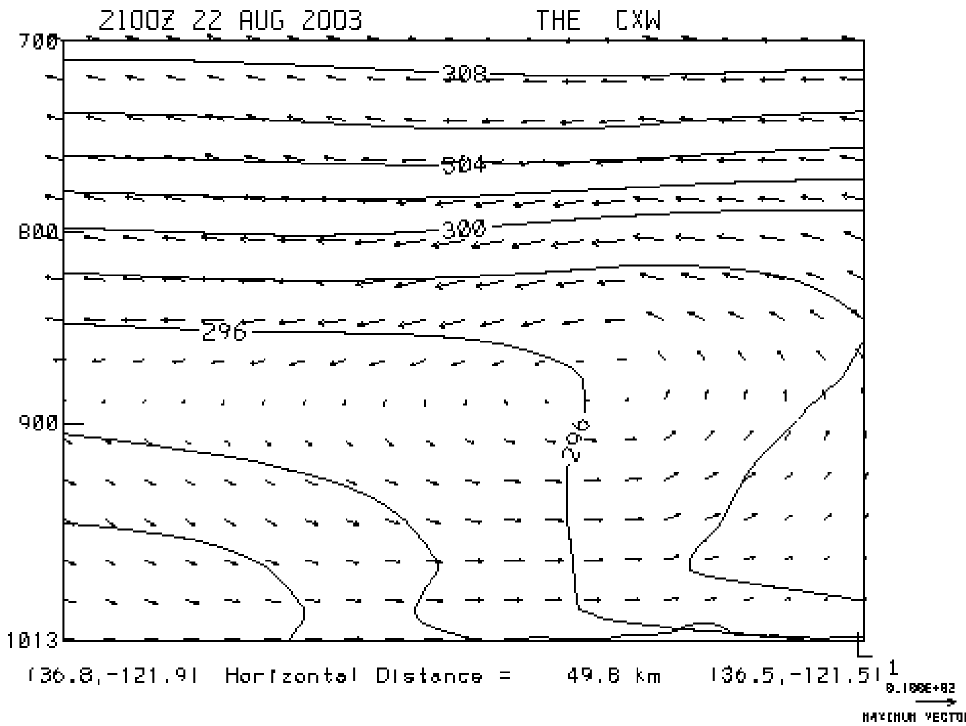


Figure 15. Vertical cross-section of theta and circulation vectors for 22 August 2003 at 21Z.

Table 4 recaps the difference in factors that help modify the sea breeze on the 22nd. The offshore flow at 850 mb on 22 August weakened the thermal gradient at the surface. The depth of the sea breeze was slightly shallower on 22 August due to the stability of the lower atmosphere on this day. The result was a weaker sea breeze on 22 August.

| 5-Aug | 22-Aug |
|---|---|
| weak onshore | moderate offshore |
| synoptic flow | synoptic flow |
| deeper heating | shallower heating |
| greater thermal | weaker thermal |
| gradient | gradient |
| slightly more stable | less stable |

Table 4. Difference in factors between 05 & 22 August 2003.

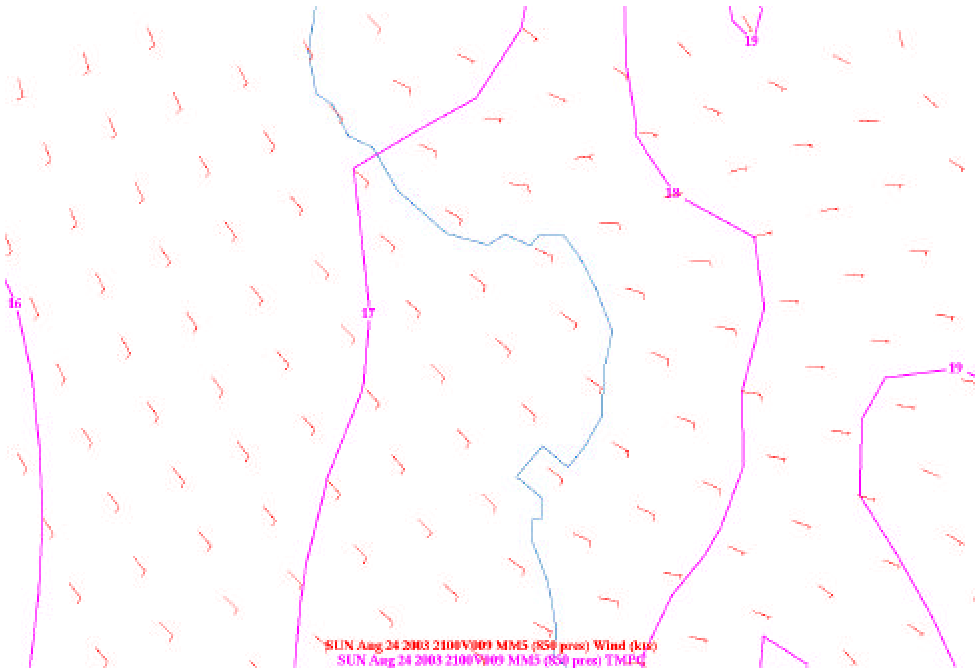


Figure 16. 850 mb winds for 24 August 2003 at 21Z

### 2. Comparison Case Two: 24 vs. 05 & 22 August 2003

To investigate the impact of low-level thermal structure evolution on the sea breeze, 24 August was examined relative to 05 August (reference day) and 22 August. The synoptic-scale flow at 850 mb on 24 August was very similar to that on 22 August as seen by comparing figures 12 and 16. On both days southeasterly flow was occurring across the region, which tended to oppose the surface sea breeze on 22 August and resulted in a relatively weak surface thermal gradient on that day. In contrast, the surface thermal gradient and sea breeze strength was much stronger on 24 August and rather similar to 05 August as seen in figures 11 and 17. Both days produced wind directions of 270$^{o}$ over the bay with surface wind speed of about 15 knots by 21Z. The primary difference on these plots is in the characteristics of the thermal gradient. The orientation of the thermal gradient on 24 August was primarily the same as the 5$^{th}$ (concave around the bay), but was strongest in the northeast area of the bay. The gradient has increased surface temperatures, particularly in the northern bay area reaching 28$^{o}$ C, compared to only 22$^{o}$ C on the 5$^{th}$. This is an artifact of the northwesterly, synoptic-scale flow at the surface on the 24$^{th}$.

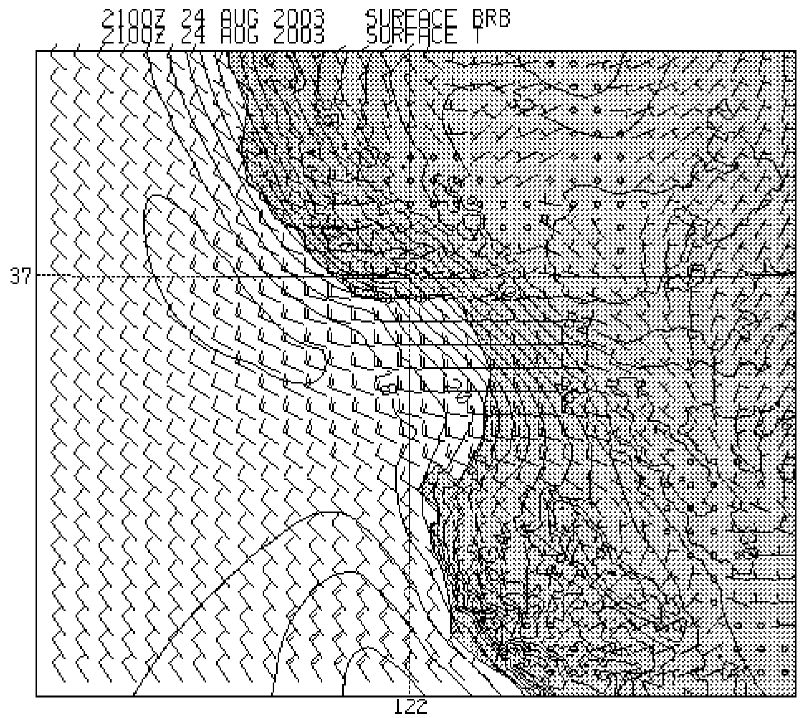


Figure 17. Horizontal surface plot of temperature ($^{o}$ C) and wind speed (knots) for 24 August 2003 at 21Z.

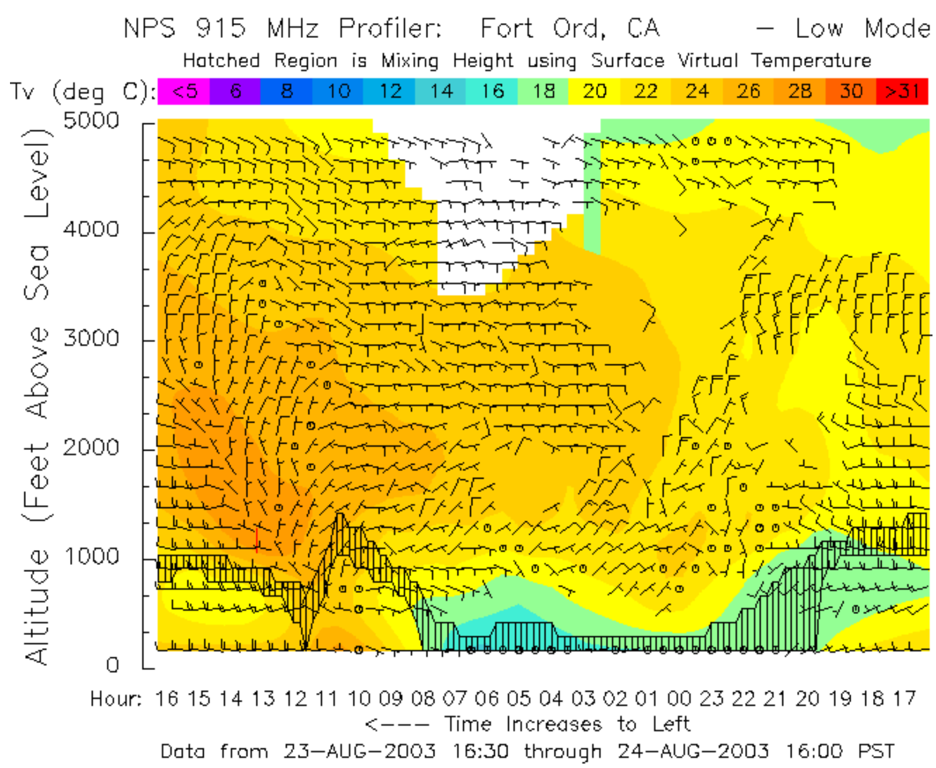


Figure 18. Profiler image for 24 August 2003. (From: Lind 2003)

The depth of the sea breeze and the thermal evolution over time are shown by the profiler image of 24 August (figure 18). The profiler reveals that the atmosphere is much warmer above the surface on 24 August than either 05 August (figure 10) or 22 August (figure 14). At 12Z (0500 PST) on the $24^{th}$, an inversion occurs at the surface. By 21Z (1400 PST), the inversion has raised to 1000 feet (ASL). Even though the surface temperature at 12Z is two degrees lower on August 24, both temperatures reach $24^{o}$ C nine hours later. The degree of heating above the surface on 24 August compared to the $5^{th}$ is considerably different with $28^{o}$ C at 1000 feet (ASL) on 24 August compared to only about $18^{o}$ C on 05 August. This indicates the development of a strong, low-level inversion, which was not evident on 05 August (figure 10) or 22 August (figure 14). Satellite imagery revealed cloud-free days for both 05 and 24 August.

The cross-section plots of potential temperature and circulation vectors illustrate the differences in the depth of the sea breeze and thermal structure caused by the inversion on 24 August. 24 August (figure 19) is more weakly stratified above 900 mb compared to the $5^{th}$ (figure 9), and the $308^{o}$ K line is lowered substantially on the $24^{th}$, indicative of the strong warming and inversion. Cross-section winds and the profiler show the depth of the sea breeze on 24 August to be slightly lower than on 05 August. The profiler image also shows how the sea breeze deepened over time. According to the profiler, the sea breeze began around 1000 PST on 24 August and was confined to a very low level. It gained strength and continued to rise to about 2000 feet (ASL) by 21Z. Over the next few hours the sea breeze continued to increase in depth increase, reaching 2300 feet (ASL) by 1630 PST.

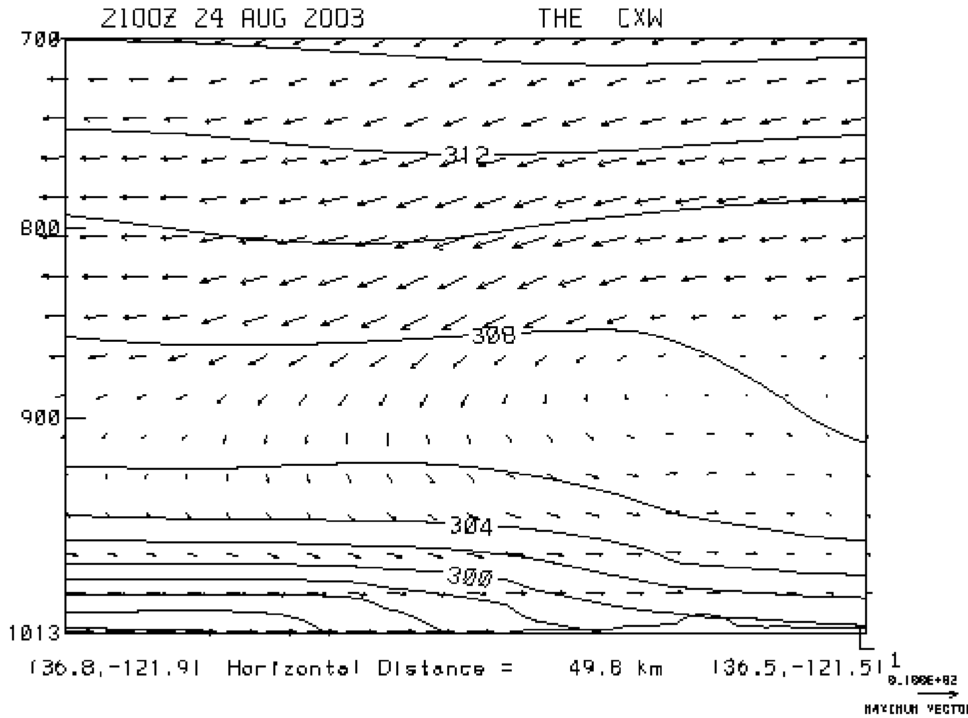


Figure 19. Vertical cross-section of theta and circulation vectors for 24 August 2003 at 21Z.

Additionally, the temperature difference plot (figure 20) illustrates the strong heating that occurred on the 24th. Positive values are present throughout the vertical column, indicating that the entire layer is heated between 12Z and 21Z. On 05 August, heating occurs over a much shallower layer during the nine hours, up to about 875 mb (figure 21). Despite this difference, the cross-coast gradient vanishes at about 900 mb on both days. This indicates a similar depth of forcing and sea breeze. 24 August had a stronger low-level thermal gradient but similar sea breeze because heating was confined to the lowest layers.

22 August offshore surface winds at 12Z (figure 22) were the same as the 850 mb winds while on 24 August the 12Z surface winds (figure 23) are from the opposite direction. This is consistent with the presence of an inversion and tends to produce onshore flow that may offset some of the strong thermal forcing.

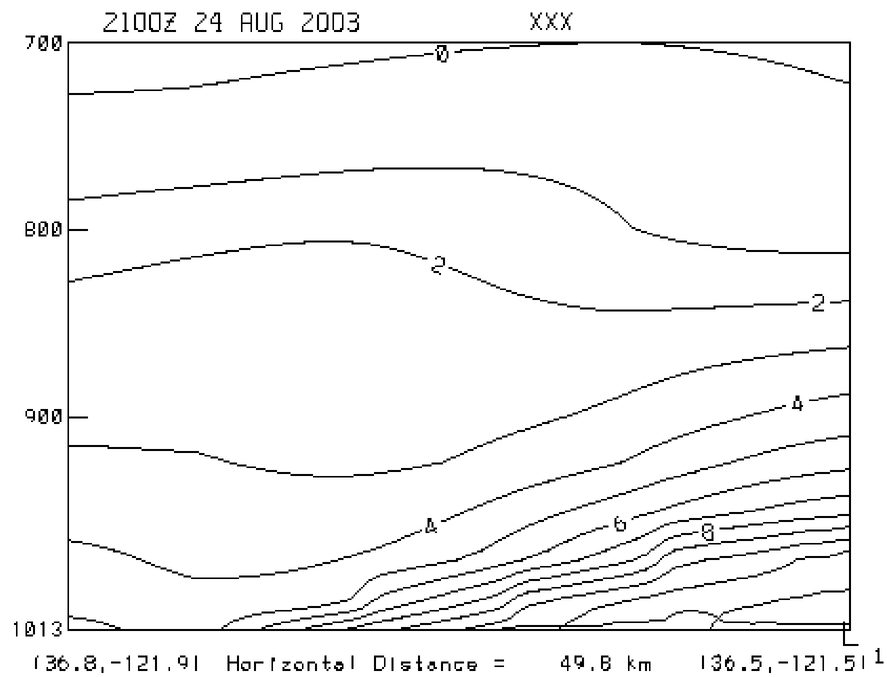


Figure 20. Temperature difference plot for 24 August 2003.

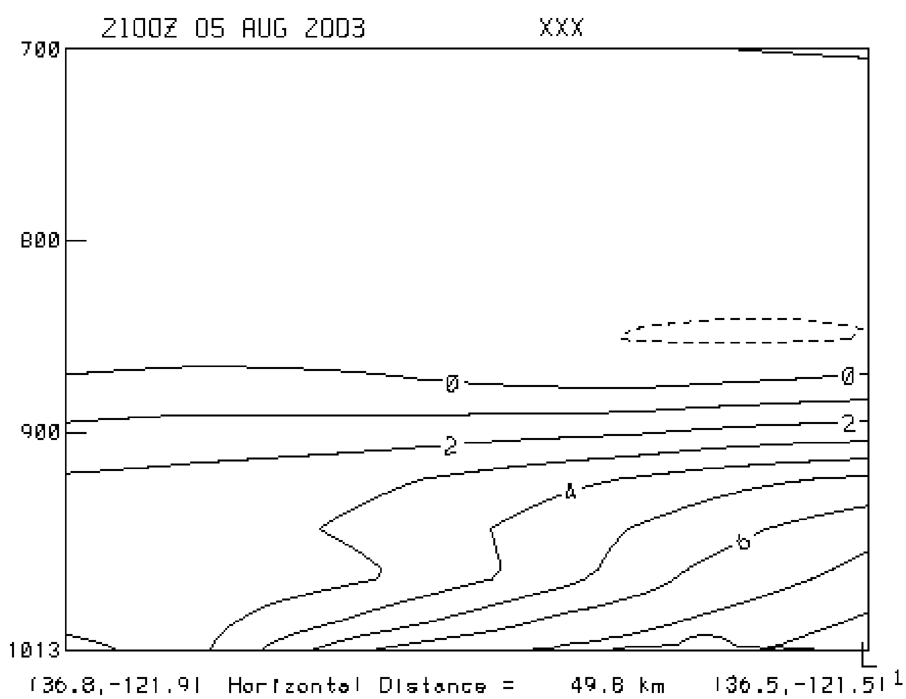


Figure 21. Temperature difference plot for 05 August 2003.

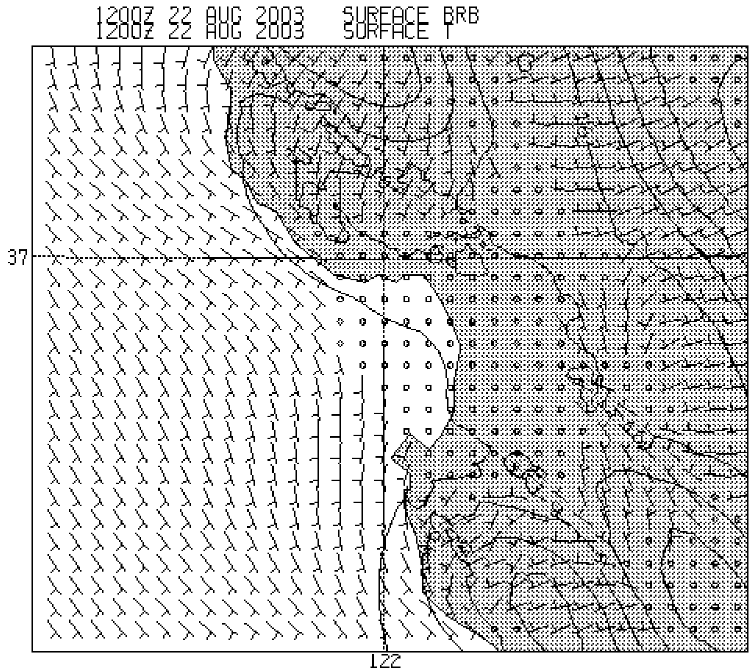


Figure 22. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 22 August 2003 at 12Z.

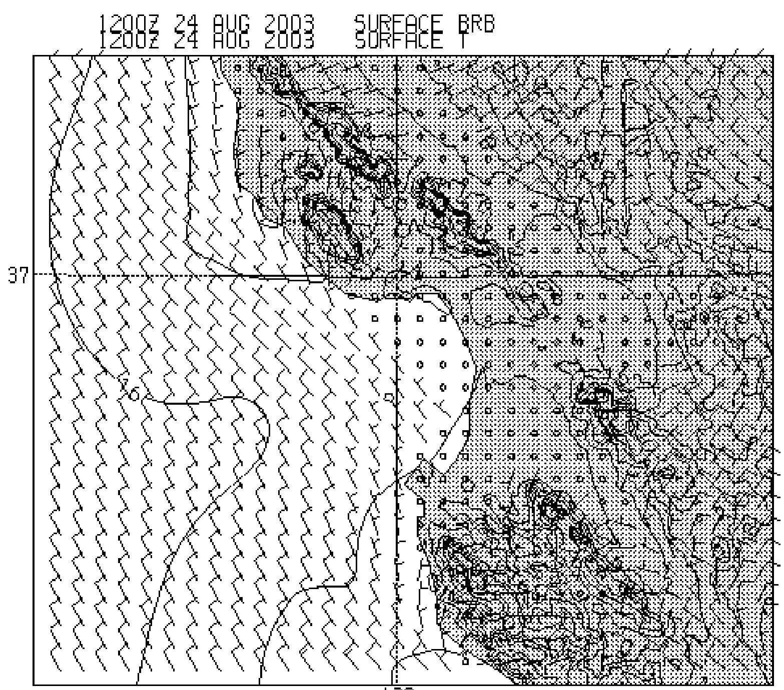


Figure 23. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 24 August 2003 at 12Z.

Table 5 recaps the factors that modify the sea breeze on August 24. The orientation of the thermal gradient was similar on 05 and 24 August, but was stronger in the northeast area of the bay on the 24th. The depth of the sea breeze on 24 August was slightly lower than 05 August due to the very shallow layer of heating on 24 August caused by an inversion that was present on that day. The result was a sea breeze that was similar in strength to August 05.

| 5-Aug | 24-Aug |
|---|---|
| weak onshore | moderate offshore |
| synoptic flow | synoptic flow |
| deeper heating | very shallow heating |
| strong thermal | slightly stronger |
| gradient | thermal gradient |
| stable | very stable at low levels |

Table 5. Difference in factors between 05 & 24 August 2003.

### 3. Comparison Case Three: 24 vs. 26 August 2003

This comparison examines how the direction of the synoptic flow influences the sea breeze. Figures 16 and 24 demonstrate the differences between 850 mb flow on 24 and 26 August. As discussed earlier, the winds at this level on 24 August were from the southeast (offshore), while surface winds were northwesterly and directed onshore. On 26 August, the synoptic-scale winds have changed direction, and are from the southwest. This results in an onshore flow situation at this level. The low-level winds off the coast were northwesterly (figure 25), similar to 24 August as seen in figure 17 at 21Z. Both days have 850 mb synoptic-scale winds of 10 knots.

Examining the surface winds and thermal structure at 21Z for 26 August (figure 25) and 24 August (figure 17), a distinct difference in the sea breeze is observed. First, the strength of the sea breeze has decreased on the 26th to 10 knots over Monterey Bay when compared to the 15-knot sea breeze on the 24th. In addition, the winds further offshore have increased to 20 knots on 26 August compared to only 10 knots on 24 August. This is indicative of strengthening synoptic-scale onshore flow at the surface.

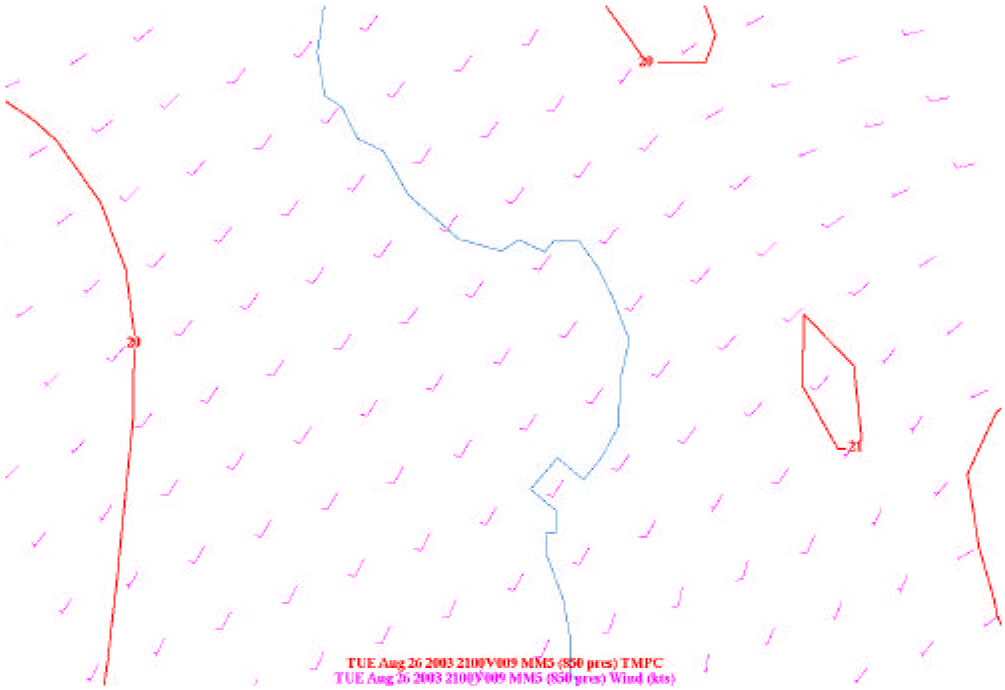


Figure 24. 850 mb winds for 26 August 2003 at 21Z.

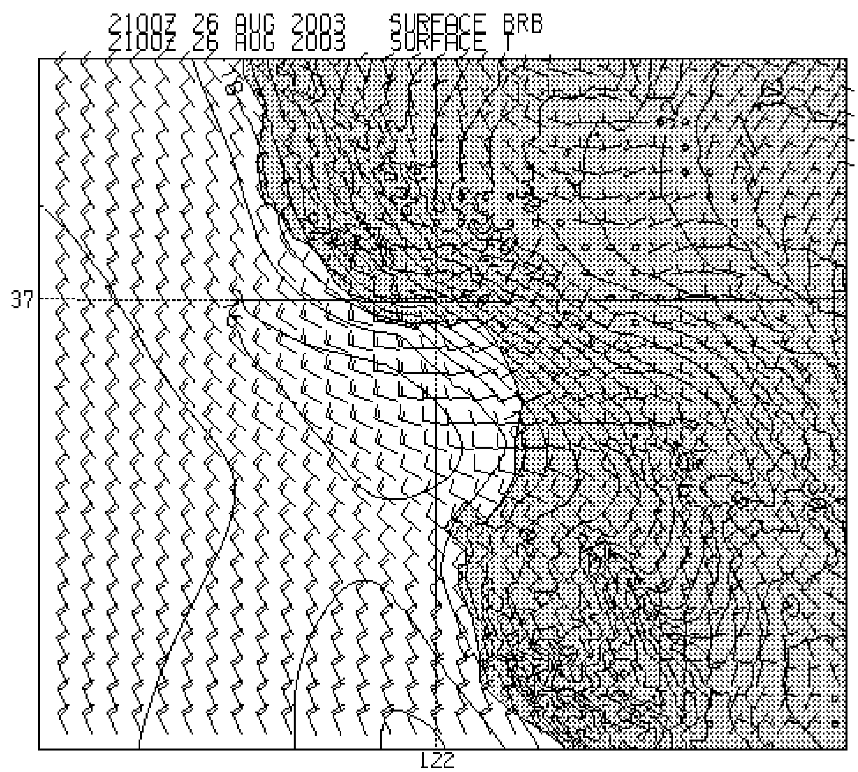


Figure 25. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 26 August 2003 at 21Z.

Second, the characteristics of the thermal gradient were different on the 26th. Cooler air has worked its way into the Monterey Bay area and south into the Salinas Valley. Focusing on the 18° C temperature contour, notice how it is much closer to the shoreline than on the 24th. 28° C temperatures in the northern bay area have decreased to 21° C. The thermal gradient has weakened slightly on the 26th, and continues to show a temperature gradient that is oriented slightly to the northeast. These thermal changes are consistent with stronger synoptic-scale northwesterly onshore flow.

The vertical cross-section of theta and winds indicates a cooler and deeper layer on 26 August compared to the 24th. Figure 26 illustrates this quite well with the 292° K contour almost to the coast and cooler temperatures over the entire lower part of the cross-section. In addition, the stable layer (inversion) was higher on this day, indicating that a deeper marine layer is present on the 26th compared to the 24th. The vertical cross-section for 24 August (figure 19) shows that the potential temperatures aloft are similar, indicating little synoptic change, however, 26 August is more weakly stratified above 850 mb.

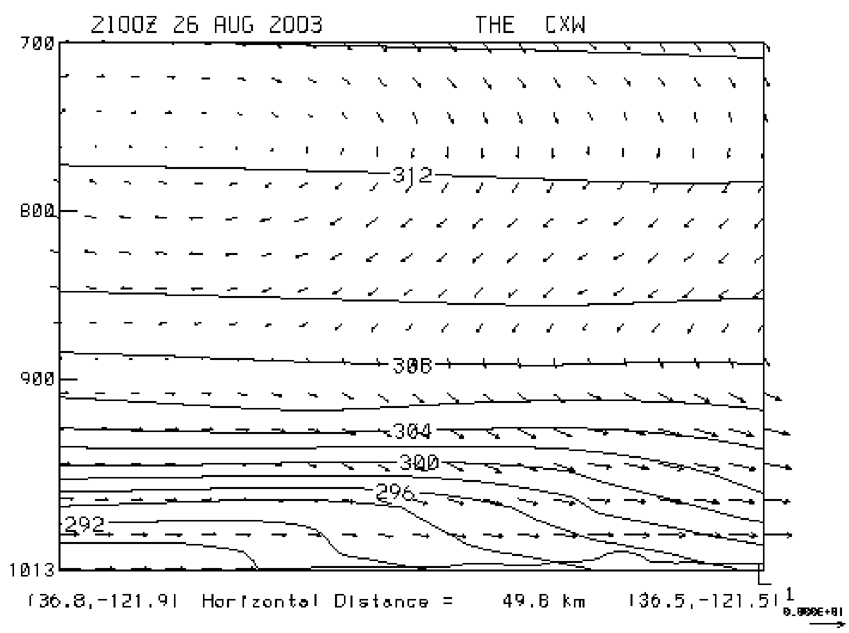


Figure 26. Vertical cross-section of theta and circulation vectors for 26 August 2003 at 21Z.

The character of the sea breeze has changed substantially on the $26^{th}$ compared to the $24^{th}$. Although the depth of the sea breeze is similar for both days, the region of strongest winds have moved inland on 26 August but remained over the bay and immediate coast on 24 August. This region of strongest winds is consistent with the location of the strongest thermal gradient which is also displaced inland. In addition, the depth of stronger onshore flow was greater on the $26^{th}$ even though the depth of the entire circulation is similar on both days. This may be due to the additional onshore flow occurring on the synoptic scale. The upper-level winds on the cross-section plots for 24 and 26 August were very different, and explain how the synoptic flow at upper-levels did not play a role in modifying the sea breeze circulation. Minimal return flow was observed on 26 August, unlike 24 August.

The profiler images clearly show the differences between these two days. The profiler image for 26 August (figure 27) shows the cooler temperatures at the surface throughout the day and a well-defined marine layer. The near surface temperatures do rise by 21Z to force the sea breeze but this warming occurs only in a shallow layer. On 24 August an inversion was also present at the surface at 12Z, which rose to 1000 feet (ASL) nine hours later. The layer below the inversion on the $24^{th}$ was considerably warmer and shows a deeper layer of heating.

Differences in the 12Z surface winds aid in modifying the sea breeze. At 12Z, both 24 and 26 August (figures 23 and 28) had northwesterly surface flow; however, it was stronger on the $26^{th}$. The combination of onshore synoptic flow at 850 mb and onshore flow in the boundary layer weakened the sea breeze on the $26^{th}$ by advecting cooler air inland to limit the diurnal heating.

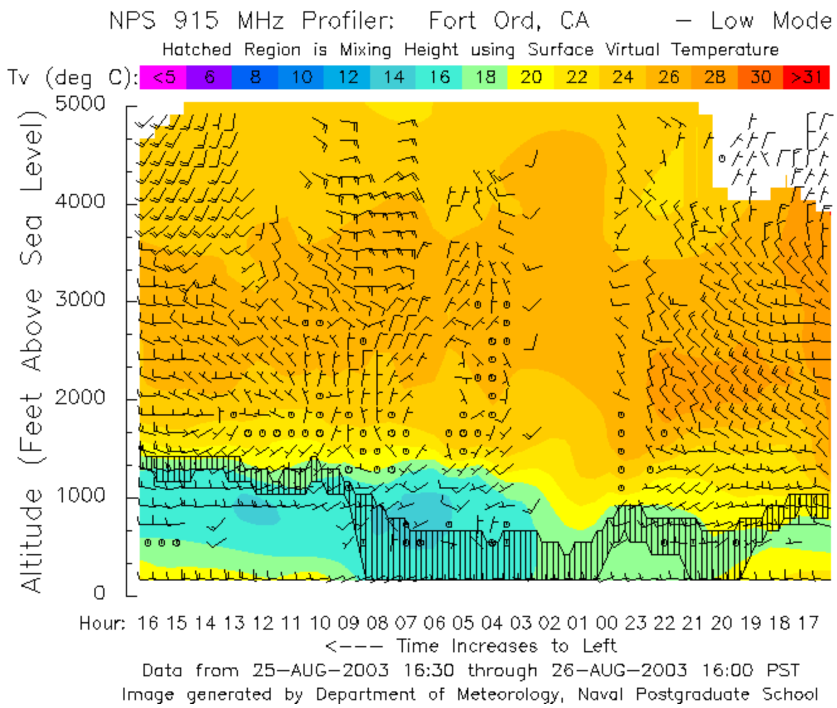


Figure 27. Profiler image for 26 August 2003. (From: Lind 2003)

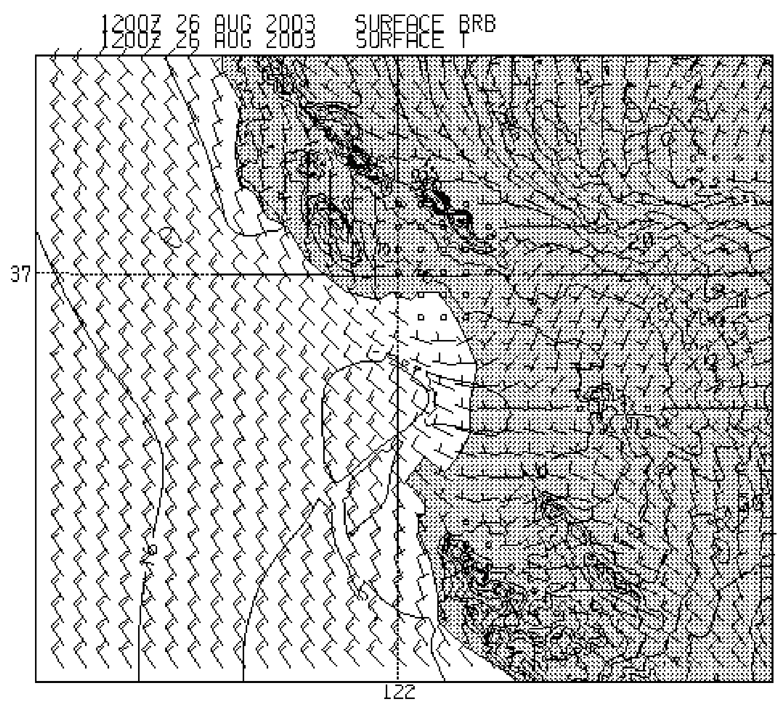


Figure 28. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 26 August 2003 at 12Z.

The lack of heating below the inversion was also limited by cloud cover, which subsequently affected the sea breeze response. On 24 August, cloud cover was not present and strong heating occurred; however clouds did occur on the 26th. Some heating occurred as clearing took place throughout the day.

Characteristics of the vertical wind structure of the sea breeze are different on these days. On 24 August (figure 18) there was a distinct sea breeze of 15 knots that initiates near the ground and deepens over time. Winds above the sea breeze layer remained around 5 to 10 knots from the north to northeast. Examining 26 August (figure 27), the surface winds (sea breeze) were weaker at 10 knots, and were not as distinct from the northwesterly synoptic-scale winds that occurred through the layer up to about 3000 feet (ASL). This lack of a well-defined diurnal sea breeze below the inversion is consistent with the lack of diurnal heating through a deep layer.

Table 6 summarizes the factors that help modify the sea breeze on 26 August. The combination of onshore flow at 850 mb and onshore synoptic-scale flow at the surface, along with the cool marine layer on the 26th resulted in a sea breeze that was weaker than on the 24th and the 5th.

| 24-Aug | 26-Aug |
|---|---|
| moderate offshore | moderate onshore |
| synoptic flow | synoptic flow |
| weaker surface winds | stronger surface winds |
| shallow layer | cooler, deeper layer |
| below inversion | below inversion |
| similar thermal | similar thermal |
| gradient | gradient |

Table 6. Difference in factors between 24 and 26 August 2003.

#### 4. Comparison Case Four: 28 & 29 vs. 26 August 2003

To further explore the impact of the depth of the marine layer on the evolution of the sea breeze, 26 August was compared to 28 and 29 August, where a deeper intrusion of cooler air into the Monterey Bay region occurs. In the previous discussion of the last case, a decrease in temperatures near the surface occurred on the 26th compared to the other days that were studied due to

the marine layer, low-level onshore flow, and clouds. The profiler time series for these three days are shown in figures 27, 29, and 30. All three days show the presence of a cool marine layer, which is deeper on the 28th and 29th than the 26th. There is a decrease in surface temperatures over the three days with 26 August having a 20° C surface temperature at 21Z (1400 PST). Surface temperatures at 21Z (1400 PST) have decreased to 18° C on the profiler image for the 28th (figure 29). Temperatures on 29 August continue to decrease by 2° C at the profiler site (figure 30). The surface temperature at the analysis time, 21Z, is now 16° C. This drop in surface temperature at the profiler site indicates progressively less heating over the three days.

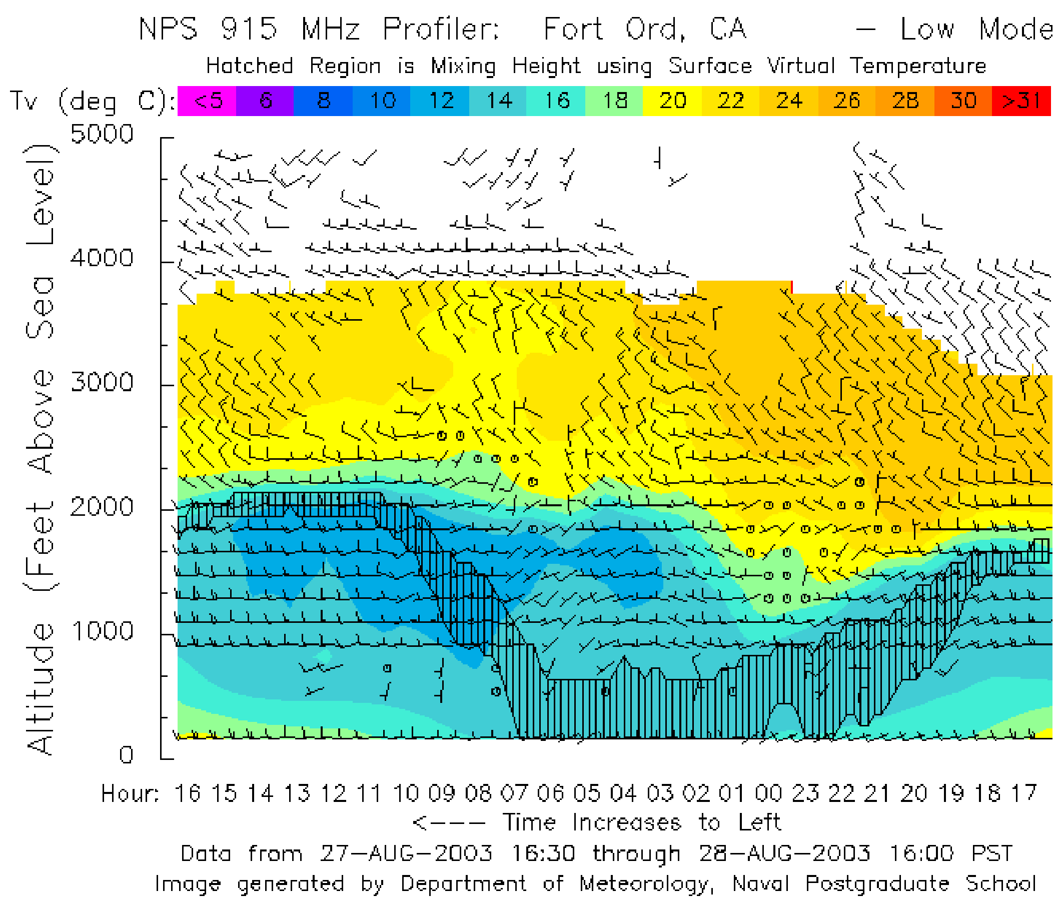


Figure 29. Profiler image for 28 August 2003. (From: Lind 2003)

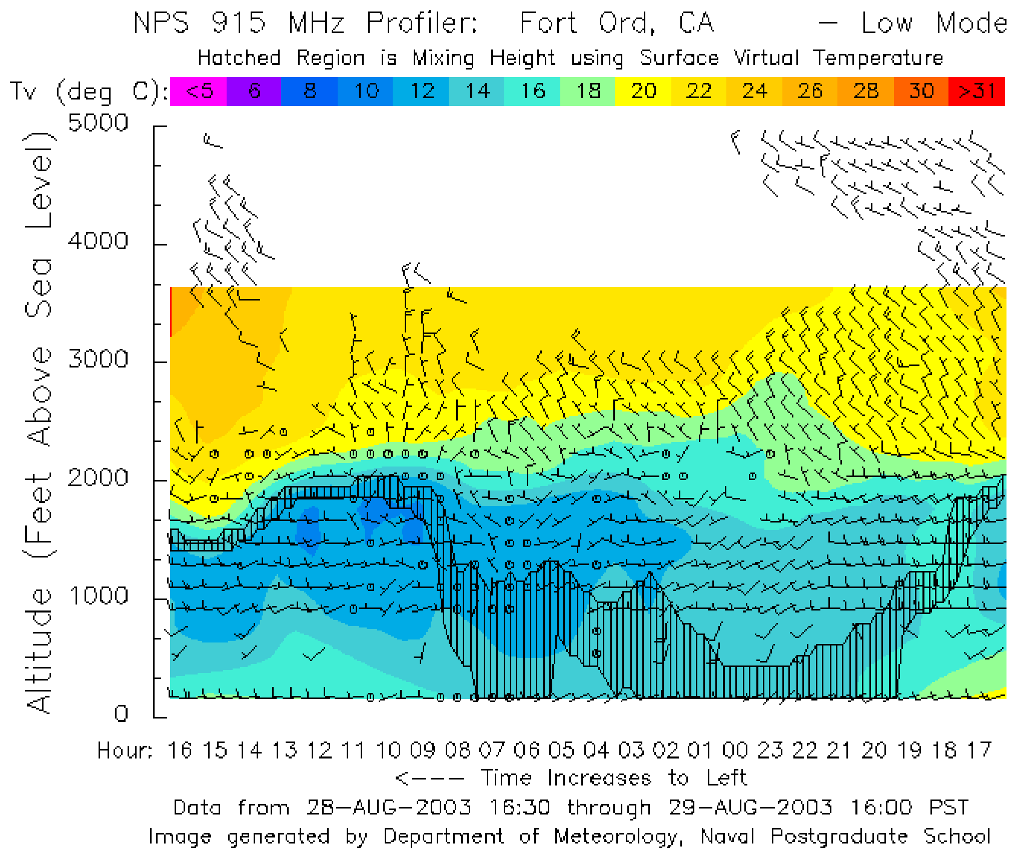


Figure 30. Profiler image for 29 August 2003. (From: Lind 2003)

The diminished heating at the profiler site was also evident on the horizontal analyses at 21Z as a progressively weaker cross-coast thermal gradient. The thermal gradient on 26 August (figure 25) was stronger over the northern bay and more diffuse over the Salinas Valley. On 28 and 29 August (figures 31 and 32), a similar temperature distribution occurred but temperatures were less over the water and the thermal gradient was weaker all around the bay. This confirms the lack of heating over the inland areas on these days as suggested by the profiler time series.

Looking at the sea breeze itself, the horizontal surface plots of all three days show that the winds decreased as the surface cooling increased. The sea breeze had an equal intensity of 10 knots on 26 and 28 August. On the 29$^{th}$, the

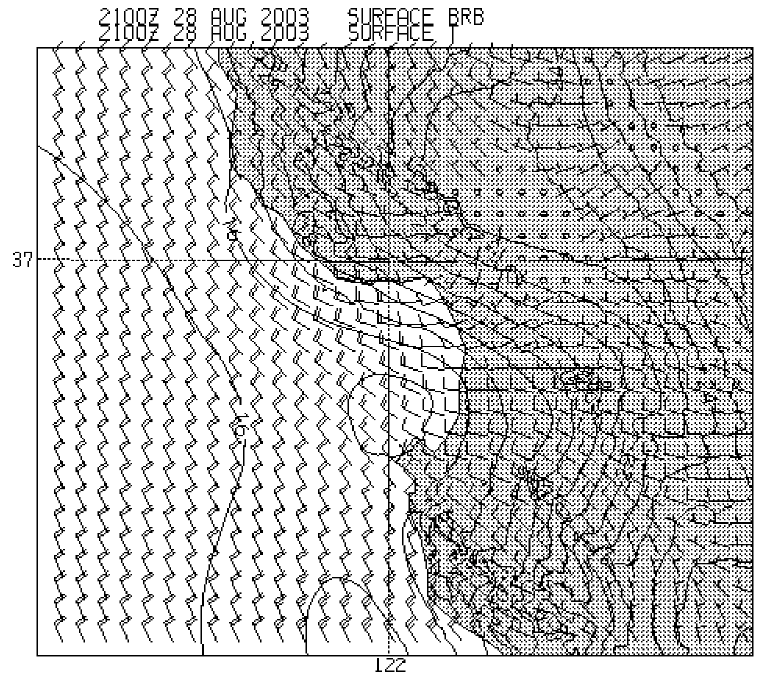


Figure 31. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 28 August 2003 at 21Z.

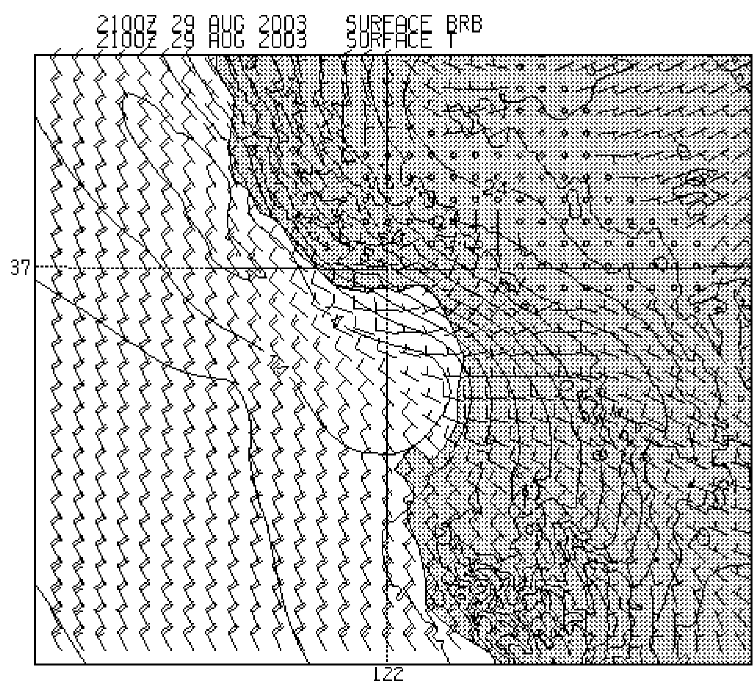


Figure 32. Horizontal surface plot of temperature ($^{o}$C) and wind speed (knots) for 29 August 2003 at 21Z.

strength decreased to 5 knots. The direction was similar for all three days. The vertical structure of the sea breeze on the profiler images show that the sea breeze (onshore flow) was poorly defined on 26 and 29 August, and was much stronger on 28 August. On all three days, the onshore flow was a combination of the synoptic scale and the sea breeze. The synoptic-scale flow below the inversion was apparently the same, as offshore winds were 20 knots on all three days. Thus, the stronger onshore flow (figure 31) seems to be a diurnal, or sea breeze response on 28 August.

Cross-sections of theta and circulation vectors at 21Z also illustrate the difference in sea breeze depth and strength. Figure 33 is a cross-section for 28 August, and it shows onshore flow from the surface up to 800 mb with winds weakening aloft. According to the MM5 model, the 850 mb (synoptic) flow is light (< 5 knots) and from the south (figure 34). The sea breeze is shallow on the 29$^{th}$, reaching to 925 mb (figure 35). Synoptic-scale flow for this day is from the northeast, or offshore, and the strength of the synoptic-scale flow is on the order of 5 knots (figure 36). Comparing these two days to 26 August (figure 26), the sea breeze circulation reached about 925 mb. Recall that the synoptic flow on the 26$^{th}$ is onshore with strength of 10 knots.

The vertical structure of the temperature and sea breeze on these three days suggest that a moderately deep marine layer (26 and 29 August) was less conducive to a sea breeze (strong onshore flow in the pm) than the deeper marine layer on the 28$^{th}$. The difference in sea breeze depth and intensity on 28 August may be due to the strong (20 knots) northwesterly synoptic winds seen at the surface or could be explained by cloud cover. Cloud cover for 26, 28, and 29 August was the same. Early in the day clouds were present and some clearing took place by the 21Z analysis time. Another possible explanation is that with the deeper marine layer, a moderate but deeper thermal gradient is established which offsets the effect of the cooling and the weaker thermal gradient evident on the surface chart (figure 31). This suggests the importance of knowing the full vertical evolution of the thermal structure to gauge the sea breeze intensity.

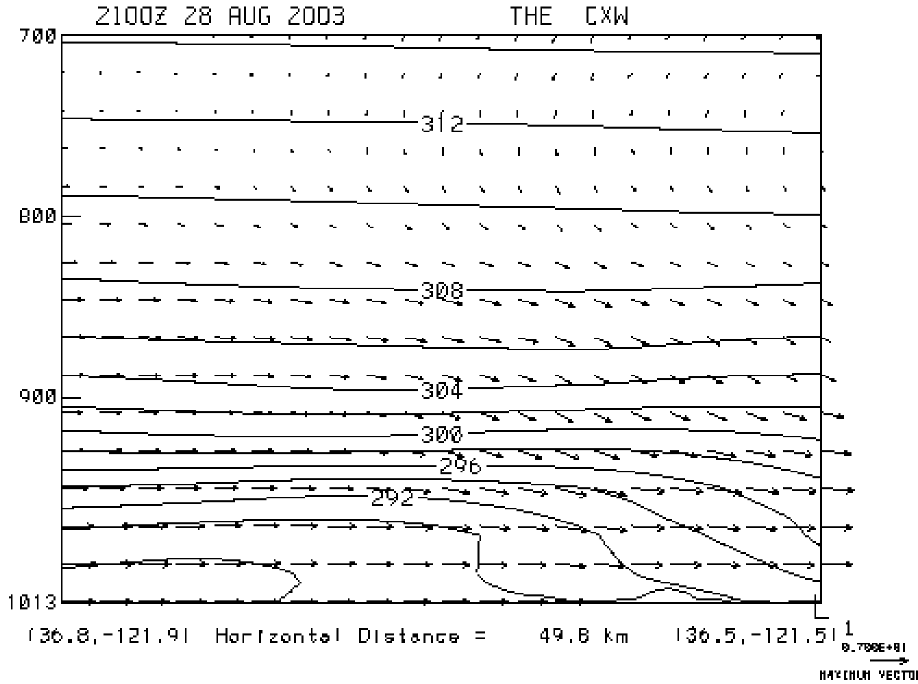


Figure 33. Vertical cross-section of theta and circulation vectors for 28 August 2003 at 21Z.

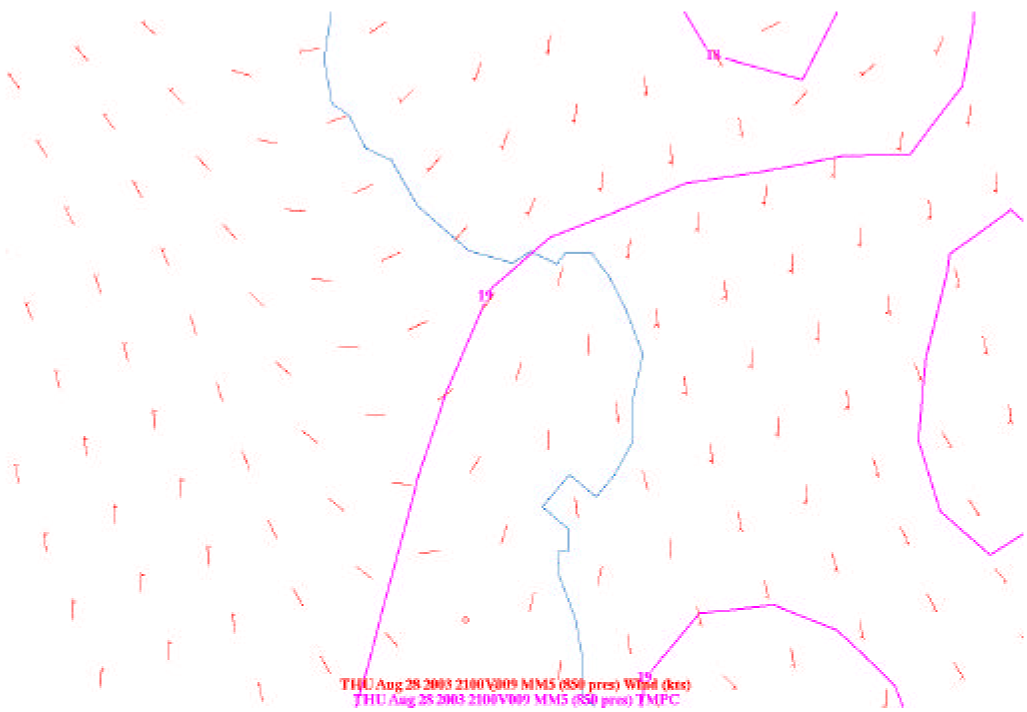


Figure 34. 850 mb winds for 28 August 2003 at 21Z.

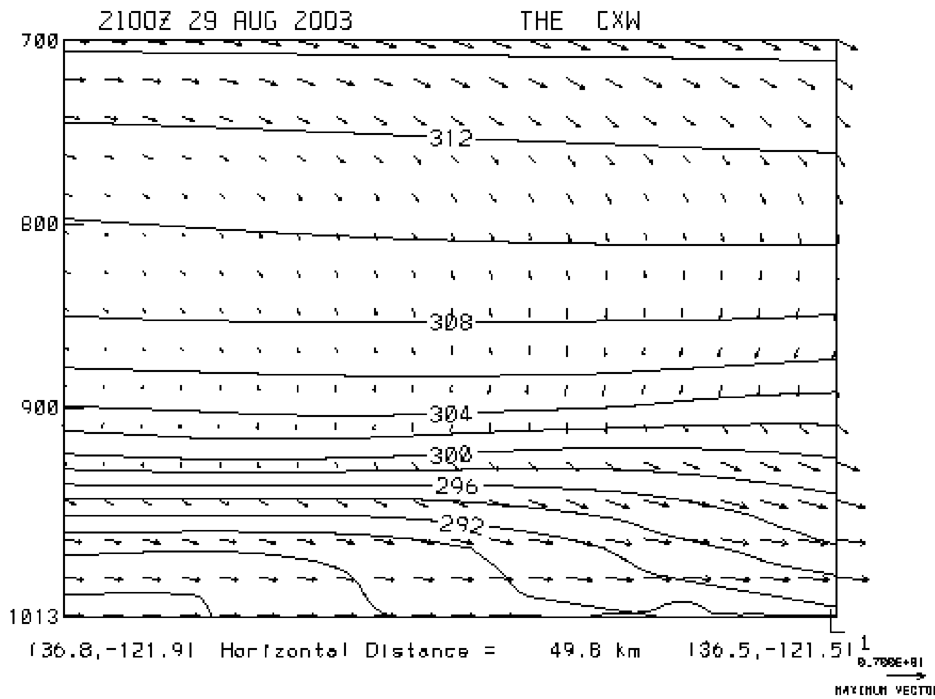


Figure 35. Vertical cross-section of theta and circulation vectors for 29 August 2003 at 21Z

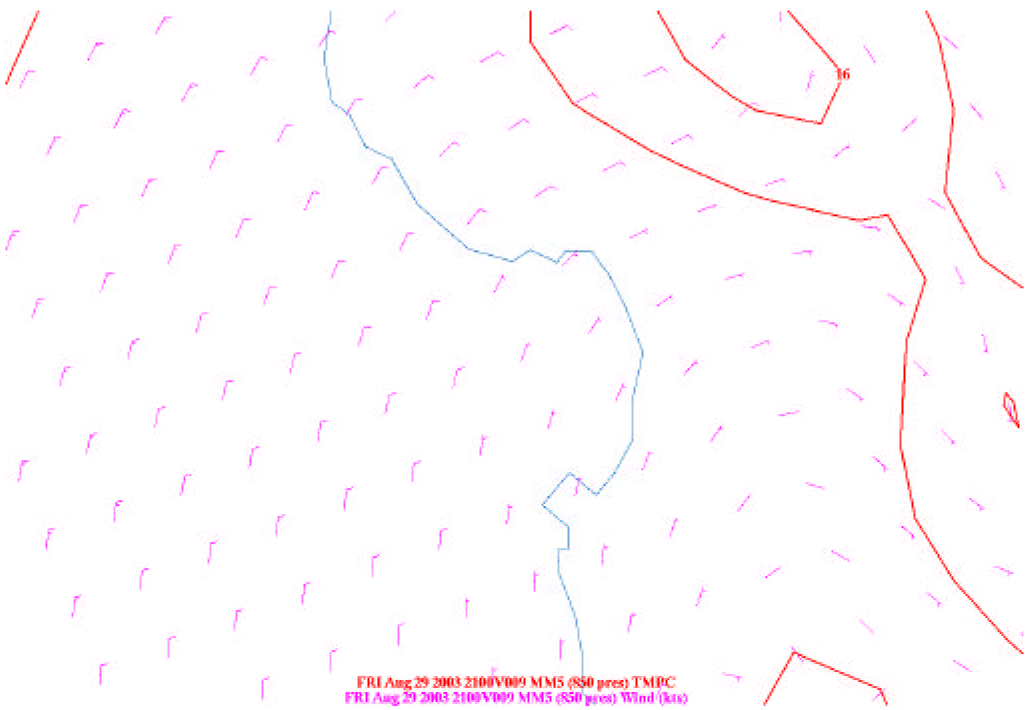


Figure 36. 850 mb winds for 29 August 2003 at 21Z.

Table 7 summarizes the factors that aid in modifying the sea breeze on 26, 28, and 29 August. Temperatures near the surface continued to cool around the Monterey Bay from 26-29 August. The presence of an inversion limited the heating to a shallow layer and weakened the thermal gradient, which reduced the strength of the sea breeze. As the temperature decreased on the 29th, so did the depth and strength of the sea breeze circulation. The result was a sea breeze that was of the same strength on the 26th and 28th, but decreased in the bay by 5 knots on the 29th.

| 26-Aug | 28-Aug | 29-Aug |
|---|---|---|
| moderate onshore synoptic flow | weak southerly synoptic flow | weak offshore synoptic flow |
| strong northwesterly surface winds | strong northwesterly surface winds | strong northwesterly surface winds |
| shallower inversion, cool surface temps | deeper inversion, cooler surface temps | similar inversion (to 28th) coolest surface temps |
| stronger thermal gradient | weaker thermal gradient | similar thermal (to 28th) gradient |

Table 7. Difference in factors between 26, 28, and 29 August 2003.

# V. SUMMARY AND CONCLUSIONS

## A. CONCLUDING REMARKS

Sea breezes are a common occurrence, and are an important influence on coastal weather, climate, and air quality. Although it appears to be a simple phenomenon, it is useful to understand the meteorological conditions that have a role in modifying the sea breeze. Using available surface observations, aircraft and profiler data, and MM5 model outputs; a method was developed using comparative case studies to study the impact of various modifying effects on the structure of the Monterey Bay sea breeze during August 2003. Six days were identified that had conditions favorable for comparison and were used to form contrasting case studies that could be related to previous studies. This paper reflects how the sea breeze depth and strength have been impacted by factors such as synoptic-scale flow, thermal gradient intensity, and the degree of heating.

### 1. Impact of Synoptic-Scale Flow

The impact of the synoptic-scale background flow has been studied extensively under various scenarios both observationally and numerically (Nuss 2003). Estoque (1962) demonstrated how the basic sea breeze is modified by offshore flow at 5 m $s^{-1}$. Advection of warm air towards the sea creates a strong thermal gradient that is sufficient to generate a sea breeze. Stronger subsidence offshore is evident for this scenario, another difference from the basic circulation. The strength and depth of the sea breeze was reduced for this case, as well as inland penetration.

Research from the current study produced similar results. Comparison case one illustrated how offshore synoptic flow of 10-15 knots (5.1-7.7 m $s^{-1}$) reduced the strength of the sea breeze. In the absence of any synoptic flow, the sea breeze wind direction will depend only on the local coastline orientation. However this is not the case for Monterey Bay and in many instances, the sea breeze was from 270$^{o}$. Only on a few days does the sea breeze direction vary

throughout the bay, blowing perpendicular to the concave coastline at all points along the bay. This aspect was not discussed in any of the references mentioned in this thesis because most of those studies were performed along straight coastlines.

Profiler data showed how the depth of the sea breeze decreased when offshore synoptic background flow was present. Although there was no evidence of stronger subsidence offshore, return flow aloft is obvious during the offshore situation, analogous to Estoque's (1962) study. Cross-section plots revealed how the offshore synoptic flow has shortened the horizontal length scale of the sea breeze.

Comparison case three also illustrated the effects of synoptic-scale flow on the sea breeze, however this scenario depicted how onshore flow at 10 knots (5.1 m $s^{-1}$) impacted the structure of the sea breeze. Estoque (1962) indicated the effects of onshore flow at 5 m $s^{-1}$. Temperature advection from the sea over land inhibits heating over land, therefore, the thermal gradient becomes more spread out inland from the coast and is generally less intense than that of the basic circulation (Nuss 2003). The corresponding pressure gradient is weaker which results in a weaker circulation. Vertical motion is nearly absent.

Results of the present study show similar reactions. The strength of the sea breeze decreased when the direction of the background flow was onshore (>5 knots). Similar to the offshore situation, the direction of the sea breeze varied throughout the bay. Compared to the thermal gradient of the basic circulation, it differed in intensity and orientation. It had a northeastern orientation, with a stronger concentration in the northern bay. The synoptic flow at 850 mb was from the southwest, while it was from the northwest at the surface, so the thermal gradient orientation was most likely the result of the surface direction of the onshore flow. There was noticeable spreading of the thermal gradient in the southern section of the bay, and down into the Salinas Valley. The thermal gradient was also less intense in this area.

An important finding during this study was found on 05 August. The best representation of the sea breeze occurred when the synoptic flow was light and onshore, not when weak offshore synoptic flow was present, as previously described. This may be due to the tendency for cool temperature advection to concentrate the thermal gradient, as long as it is not so strong as to damp inland heating.

**2. Impact of the Degree of Heating**

The extreme warming of the Monterey Bay on 24 August created a stronger thermal gradient that was oriented to the northeast, unlike the isotherms that were parallel to the coastline for the basic circulation. The stronger thermal gradient most likely counteracted the effects of the offshore-directed synoptic flow at 850 mb and weak onshore synoptic flow at the surface. Offshore background flow should decrease the strength of the sea breeze, as seen in case one. However, it was shown during case two that the strength of the sea breeze remained the same as the basic pattern when weak offshore flow at 850 mb was present. But, the intense heating that occurred on 24 August was sufficient enough to form a sea breeze that was similar in strength to the basic circulation.

In the opposite sense, the lack of heating also has an impact on the structure of the sea breeze. Temperatures near the surface continued to cool around the Monterey Bay from 26-29 August. As the temperature decreased, so did the depth and strength of the sea breeze circulation. The coolest temperatures existed on 29 August in the Monterey Bay, and the strength of the sea breeze weakened to 5-10 knots.

**3. Impact of Cloud Cover**

Only the modifying influence of clouds on the sea breeze was studied for this research. It is well known that clouds are an important consequence of the sea breeze, however this aspect is not considered for this analysis.

Cooler temperatures (compared to the basic circulation) occurred during the 26-29 August time frame. Additionally, the amount of cloud cover was similar for these days. Satellite imagery shows cloud cover existing in the morning that

clears (to some extent) during the day. Clouds usually have a higher albedo than the surface beneath it, therefore reflecting more shortwave radiation back to space than the surface would in the absence of the clouds. As a result, less solar energy is available to heat the surface and atmosphere (Earth Observatory 2004). Despite the clearing, the thermal gradient is not enhanced enough to produce a strong sea breeze and temperatures remain cool in the afternoon on 29 August. However, the sea breeze is 5 knots stronger on 26 and 28 August when the temperatures were slightly warmer.

#### 4. Impact of an Inversion

Inversions tend to limit heating to a shallow layer, which in turn reduces the strength of the sea breeze. Comparison case 4 demonstrated how the low-level inversion that is common to the Monterey Bay modified the sea breeze. The presence of the cool, marine layer weakened the cross-coast thermal gradient and in turn weakened the strength of the sea breeze. These results were consistent throughout the 31 days of August 2003. It is important to note that the average sea breeze depth was around 3000 feet (ASL). This may be an artifact of the topography surrounding the Monterey Bay. The coastal mountains that are present near the Monterey Bay are on the order of 3000 feet.

Atmospheric stability is an extremely important issue in reference to air quality. Plume dispersion is often controlled by the stability of the atmosphere. Figure 36 illustrates how an unstable layer creates a looping pattern; coning occurs when a plume is released into a neutral layer; and a stable layer marked by an inversion yields a fanning pattern (Ahrens 1991).

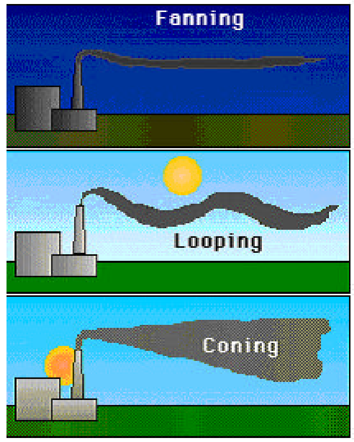


Figure 37. Example of dispersion patterns. (From: Ahrens 1991)

## B. FURTHER RESEARCH

In order to gain a fuller understanding of the Monterey Bay sea breeze, the time evolution should be researched in further detail than what was briefly discussed throughout this thesis. The complex terrain in the area may influence the timing of the sea breeze, as noted in previous studies (Banta et al 1993; Darby et al 2002). The mountains and associated valleys may contribute to early sea breeze development by producing mountain-valley circulations that add to the sea breeze (COMET 2003). After selecting the days to compare to the basic circulation, an extended time interval that covers the onset of the sea breeze and the end of the sea breeze should be studied for all the plots. These plots could also be compared to satellite imagery in order to discern how much influence the cloud degree of cloud cover actually has on the sea breeze. Comparing the time evolution of the sea breeze of the representative days would show how variant the timing of the sea breeze is (if at all).

Horizontal length of the sea breeze should be researched as well. The cross-sections used in this study are inadequate to determine how far the sea breeze penetrates inland. Local topography allows for mountain-valley flows, and channeling effects. It would be interesting to see how much of an interaction there is between the sea breeze and the other flow types. More cross-sections

should be done in different directions, especially further south into the Salinas Valley. The channeling effects of the mountains could cause the different directions of the 22 August sea breeze.

Sea breeze forcing tends to accelerate air across the coast but the presence of coastal mountains near the Monterey Bay causes the actual wind direction relative to the coast to not be across the coast (MBNMS 2004). This effect was seen during August 2003, however a few days had winds that were cross-coast. Continued work should be done on the cross-coast sea breeze, similar to the 22 August case. The same evaluation that was performed on the days in this thesis needs to be done on those that had the cross-coast winds to determine what role the mountains had in the direction of the sea breeze around the bay.

For improved results, better control on the modifying effects needs to be in place. It was hard to discern if one parameter was solely responsible for a specific result in this study. In many instances, it was a few parameters working together that modified the sea breeze. This emphasizes the usefulness of mesoscale modeling under controlled conditions to highlight and investigate these influences.

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